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ISOSTASY: A CRITICAL REVIEW

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ABSTRACT

The underlying theory pertaining to the shape of the earth is briefly reviewed. The operations and results that have led to the theory of isostasy are given. Hopfner's recent inquiry into the problem is cited in which he has shown that by means of strict potential theory isostatic reductions are highly questionable, and, furthermore, that there is no need to postulate an isostatic state in order to account for gravity data. High points of geologic and seismologic data are also cited. The conclusion is that the theory of isostasy rests upon a much more insecure foundation than has heretofore been supposed.

INTRODUCTION

A knowledge of the physical properties of the outer 100 kilometers or so of the earth is a matter of such fundamental importance that many of the most important problems of geology depend upon it for their final solution. At the same time there are few things about the earth on which there is a wider divergence of opinion among the men who have studied them than concerning the outer shells of the earth. These opinions may be divided into three rather distinct groups: (1) The outer shells of the earth behave under ordinary circumstances as a rigid body, but are occasionally folded and broken or warped by very great stresses which occur mainly in the horizontal direction. There may or may not be partial isostasy, but if there is, it is distinctly a phenomenon of secondary importance in

diastrophism. (2) The outer shells of the earth above some depth of compensation are maintained in a state of isostatic balance, i.e., every column of unit cross-sectional area above this depth has the same mass. (3) The continents are not only in a state of isostatic balance, but are also drifting about the earth on a liquid substratum.

The first opinion is rather common among geologists; the second is championed by some geodesists; and the third is more or less prevalent among certain European geologists.

Obviously not all of these can be correct. It is the purpose of the present paper to review the more pertinent data upon which the theory of isostasy is based with the intention of determining to what extent, in view of our present knowledge, such a state may safely be assumed to exist.

GRAVITATIONAL THEORY

Since most of the data pertaining to the shape of the earth and related problems are directly or indirectly based upon gravitational theory it is perhaps well that the essentials of that theory be reviewed.

Newton's law of gravitation.—Newton's law of gravitation states that every particle of mass in the universe attracts every other particle with a force proportional to the products of their masses and inversely proportional to the squares of the distances between them.

$$f = \frac{K m_1 m_2}{r^2} \tag{1}$$

where f is the attractive force, K the force between two unit masses set at unit distance apart, m_1 and m_2 the two attracting masses, and r their distance apart. Similarly the attraction of a body of mass M on a unit mass at a point P is,

$$F = K\left(\frac{m_1}{r_1^2}\cos\theta_1 + \frac{m_2}{r_2^2}\cos\theta_2 + \frac{m_3}{r_3^2}\cos\theta_3 + \cdots\right)$$

$$F = K\sum\frac{m}{r^2}\cos\theta \tag{2}$$

where m is a small element of the mass M, r is the distance between m and P, and θ is the angle between r and the force F.

Two theorems which will be found useful later on may now be stated without proof.

Theorem I.—The force on a unit mass at an outside point exerted by a spherical shell of uniform thickness and density is the same as if the entire mass of the shell were concentrated at a point at its center. The force at a point inside the shell is zero.

Theorem II.—The attractive force on a unit mass at an outside point exerted by a sphere which is homogeneous in concentric shells is the same as if all its mass were concentrated at its center.

Earth gravity.—Earth gravity, g, is defined as the attraction of the earth upon a unit mass which is rotating with the earth. Then g is the resultant of the attractive force of the earth's mass plus the centrifugal force due to the earth's rotation.

$$g = K\sum \frac{m}{r} \cos\theta + \omega^2 R \cos^2\phi \tag{3}$$

where g is gravity, ω the angular velocity of the earth, R the earth's radius, and ϕ the latitude of the point considered. The other terms are the same as in equation (2).

Earth potential.—If two particles with masses m_1 and m_2 respectively are at a distance r apart, and if m_2 is moved away from m_1 to an infinite distance, the work required is

$$V = K\frac{m_1 m_2}{r} \tag{4}$$

If a body such as the earth is at rest then the work required to move a unit mass from the vicinity of the body to an infinite distance is,

$$V = K\sum \frac{m}{r} \tag{5}$$

where m is an element of the mass of the attracting body and r the distance between m and the initial position of the unit mass.

This quantity V is known as the gravitational potential due to the attracting mass M. For every point in space there is one and only one value V due to mass M. Suppose the body of mass M is rotating about an axis with an angular velocity ω. Let P be a point on its

surface at a distance ρ from the axis of rotation. The work required to carry a unit mass against centrifugal force from the point P to the axis of rotation (while still rotating with the body) is,

$$V_c = \frac{\omega^2 \rho^2}{2} \tag{6}$$

V_c is known as the rotational potential at the point P.

Let W_P be the total potential at P. Then,

$$W_P = V_P + V_{cP} = K \sum \frac{m}{r} + \frac{\omega^2 \rho^2}{2} \tag{7}$$

Every point in space rotating with a given body has a single value for the quantity W. W_P represents the sum of the work required to carry a unit mass from P to an infinite distance away against gravitational attraction alone, plus the work required to carry the same unit mass from P to the axis of rotation against centrifugal force alone. A surface can be passed through all points having the same value for $W = W_0$ and this surface will contain only points having $W = W_0$. Such a surface is called an equipotential surface. The equipotential surfaces of the earth are closed surfaces passing around the earth, one and only one of which passes through each point in space about the earth.

Since the potential energy of a mass at every point on an equipotential surface is the same, no work is done in moving a mass along an equipotential surface. Since no work is done in moving a mass anywhere on an equipotential surface there can be no component of gravity parallel to that surface. Therefore gravity at every point is directed at right angles to the equipotential surface at that point. An equipotential surface may now be defined as a surface that is everywhere at right angles to the direction of gravity. It is thus seen to be the same as a level surface.

Let W_1 be an equipotential surface and W_2 be another a very short distance above W_1. The work required to carry a unit mass from W_1 to W_2 is the same regardless of the path taken. Let this work be ΔW. Then,

$$\Delta W = W_1 - W_2$$

Let g be the value of gravity on W_1 at a point P and d be the distance between W_1 and W_2 at P. Then,

$$gd = \Delta W = \text{a constant}$$

$$d = \frac{\Delta W}{g} \tag{8}$$

This tells us that the distance between two given equipotential surfaces is inversely proportional to the value of gravity at the point considered.

The geoid.—In considering the figure of the earth there are several surfaces that might be used. The one practically universally used is the sea-level surface of the earth, which is known as the geoid. The geoid, then, is defined as the equipotential surface of the earth coinciding with mean sea level. The ultimate problem of geodesy is the determination of the exact shape of the geoid.

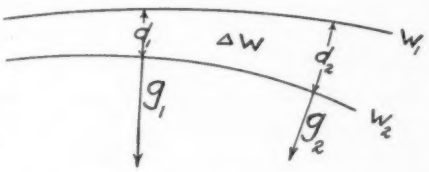

FIG. 1. The relation between the value of gravity and the distance between equipotential surfaces W_1 and W_2. $g_1 d_1 = g_2 d_2 = \Delta W$.

The direction of the normal to the equipotential surface at every place is the direction of the plumb line at that point. This direction may be determined by astronomic observation.

Astronomic latitude and longitude.—After the manner A. Prey[1] the following familiar terms may be defined so as to apply to an irregularly shaped geoid.

The equator is the locus of all points whose plumb-line directions are parallel to a plane which is normal to the axis of rotation of the earth. The locus of all points whose plumb-line directions make an angle ϕ with this plane constitutes the parallel of geographic latitude ϕ. If one places a plane in the plumb-line direction of a point on the earth's surface and parallel to the axis of the earth's rotation, then the locus of all points whose plumb-line directions are parallel to this plane is a meridian.

[1] *Einführung in die Geophysik* (1922), p. 35.

Any meridian may be chosen as a prime meridian for reference. Then the latitude and longitude so defined is known as the astronomic latitude and longitude because this is what is obtained by astronomic observation.

Geodetic measurements.—The essential principle involved in the determination of the size of the geoid by geodetic means consists in the measurements of the angle between the normals to the geoid at different stations and by triangulation of the distance between the stations. Let θ be the angle between the normals for the geoid at A and B. Let S be the length of the arc AB on the geoid and R be the radius of curvature of the geoid between A and B. Then,

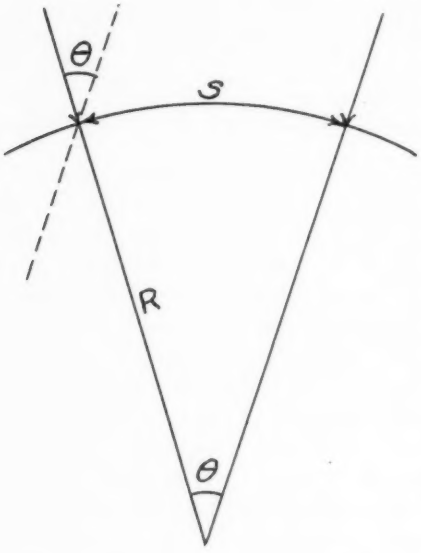

Fig. 2. How the radius of curvature R of the geoid is determined. S and θ are measured directly. Then $R=\frac{S}{\theta}$.

$$\frac{S}{R}=\theta\,,$$

or

$$R=\frac{S}{\theta} \qquad (9)$$

where θ is expressed in radians. S is obtained by triangulation from A to B.

Such measurements carried out on the continents have shown that the geoid under the continents is, as a first approximation, an oblate spheroid of revolution having a flattening ratio,

$$e=\frac{a-b}{a}=\text{about }\frac{1}{297}$$

where a is the equatorial and b the polar semi-diameter of the spheroid. Different arcs have yielded different values for e ranging from about $\frac{1}{290}$ to $\frac{1}{300}$.

Geodetic latitude and longitude.—On the basis of the above preliminary approximations to the shape of the geoid corresponding to the continents, it is customary in geodetic operations to assume that the geoid is a spheroid of revolution having certain constants and then to define the latitude and the longitude of a station and the azimuth to a second station with respect to this spheroid of reference. Then by means of triangulated distances and azimuths the latitude and longitude of all other stations with respect to this spheroid may be computed directly. The co-ordinates of a station with respect to a spheroid of reference are known as the geodetic latitude and longitude of the station.

The difference between the astronomic and the geodetic co-ordinates of a station is the angle between the normal to the geoid and the normal to the spheroid of reference at that station. This angle is known as the deflection of the vertical. The constants of the spheroid of reference are chosen by means of the method of least squares so as to make the sum of the squares of the deflections of the vertical a minimum.

It was noted in the trigonometric survey of India near the middle of the last century that the vertical in the vicinity of the Himalaya Mountains was deflected toward these mountains. The attractive effect of the mountains was computed and found to exceed considerably the observed deflection. This suggested the presence of a less than normal density of the rock beneath the mountains. Archdeacon Pratt of Calcutta and Sir G. B. Airy, Astronomer Royal, each attempted to account for this phenomenon.

Pratt[1] postulated that the earth's crust is supported at a uniform

[1] J. H. Pratt, "On the Attraction of the Himalaya Mountains and of the Elevated Regions beyond Them, upon the Plumb Line in India." *Royal Soc. Phil. Trans.*, Vol. CXLV (1855), pp. 53–100; "On the Deflection of the Plumb Line in India Caused by the Attraction of the Himalaya Mountains and the Elevated Regions Beyond; and Its Modification by the Compensation Effect of the Deficiency of Matter below the Mountain Mass," *ibid.*, Val. CXLIX (1859), pp. 745–78; "On the Influence of the Ocean on the Plumb Line in India," *ibid.*, pp. 779–96; "On the Constitution of the Solid Crust of the Earth," *ibid.*, Vol. CLXI (1871), pp. 335–57.

depth below sea level on liquid subcrustal material. The average density of the crustal columns varies horizontally in such a manner that all crustal columns of the same cross-sectional area have the same masses.

Airy's[1] hypothesis stated that the crust is resting on a denser substratum, but the crust itself has a constant density throughout. Perfect equilibrium is assumed to be maintained by the higher land columns sinking proportionally deeper into the subcrust than the shorter oceanic columns.

Hayford,[2] of the United States Coast and Geodetic Survey, computed the horizontal component at each primary triangulation station due to all the topography within a radius of 4,126 kilometers. In this computation the mass of the land was considered as a mass surplus and the sea, due to its smaller density, as a mass deficiency. The result here, as in the case of the Himalayas, was that the observed deflection was considerably less than the result computed from the visible topography.

Hayford then adopted a form of the Pratt hypothesis with the depth of compensation as an unknown quantity to be determined. He found that the sum of the squares of the residuals—deflections (observed) minus deflections (computed)—was a minimum for the depth of about 113.7 kilometers. He also found that two or three other forms of isostatic hypothesis gave him equally good results.

EARTH GRAVITY

Clairaut theorem.—There is a theorem attributable to Clairaut[3] which states that if the earth rotates about its principal axis of inertia and its form is a nearly spherical figure of rotation about that axis, then,

$$e+\beta=\tfrac{5}{2}c \qquad (10)$$

[1] G. B. Airy, "On the Computation of the Effect of the Attraction of Mountain Masses as Disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys," *ibid.*, CXLV (1855), 101–4.

[2] John F. Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States," *U.S. Coast and Geodetic Surv.* (1909).

[3] Al. Cl. Clairaut, *Théorie de la Figure de la Terre* (Paris, 1743).

where

$$e=\frac{a-b}{a}=\text{flattening or ellipticity of the earth}$$

$$\beta=\frac{g_b-g_a}{g_a}=\frac{\text{gravity at pole minus gravity at equator}}{\text{gravity at equator}}.$$

$$c=\frac{\omega^2 a}{g_a}=\frac{\text{centrifugal force at equator}}{\text{gravity at equator}}$$

This can be developed so as to give the gravity at latitude ϕ of such a body.

$$\gamma=g_a[1+(\tfrac{5}{2}c-e)\sin^2\phi].$$

Let $b_1=\frac{5}{2}c-e$

Then,

$$\gamma=g_a(1+b_1\sin^2\phi) \qquad (11)$$

where γ is the value of theoretical gravity at latitude ϕ, g_a the value of gravity at the equator, and b_1 a constant. By means of the method of least squares the best values for g_a and b_1 may be found from gravity stations taken all over the earth.

Clairaut's theorem and equation (11) are derived by neglecting magnitudes of the order of e^2. Helmert[1] has refined the theorem by retaining the magnitudes of the order of e^2. This gives,

$$\gamma=g_a(1+b_1\sin^2\phi+b_2\sin^2 2\phi) \qquad (12)$$

for which the constants are determined in the same manner as for (11). Each gravity observation must be properly reduced to sea level and should be weighted in proportion to the area of the earth that it represents. There is some question about the proper method of reduction to sea level and this will be considered more fully later in this article.

When the constants for (12) are determined from a large number of properly weighted and reduced gravity observations from all parts of the earth, the theoretical gravity so obtained is that which would

[1] F. R. Helmert, "Die normale Teil der Schwerkraft in Meeresniveau," *Sitzungsberichte der Preussischen Akademie der Wissenschaften* (1901), p. 328.

exist if the earth were a sort of mean spheroid which most nearly fits the geoid as a whole.

GRAVITY REDUCTIONS AND ANOMALIES

Gravity observations on the earth are not directly comparable because of differences in the latitude and elevations of the different stations. These difficulties may be eliminated by reducing the observed values to the level of the spheroid (for which the ideal gravity, γ, is given by the Helmert formula) and then comparing the observed value so reduced with the theoretical value, γ, for the latitude in question. The difference: *Gravity (observed and reduced)* minus *theoretical gravity* equals *the gravity anomaly.*

There are several commonly used methods of gravity reduction which will be treated briefly. Each kind of reduction, of course, yields its corresponding gravity anomaly. Therefore, the term gravity anomaly is meaningless unless the method of reduction used in obtaining it is stated.

All the reductions given immediately following have been made with one fundamental assumption, namely, *that the spheroid for which γ is computed coincides with the geoid at the station considered.* Hence all these reductions are made to sea level.

The different methods of gravity reduction that have been commonly used consist of various combinations of a few specific corrections for various influences. These are mainly corrections (1) for height above sea level, (2) for the attractive effect of the topography, and (3) corrections for the density excesses and deficiencies below sea level according to the various hypotheses of isostasy.

The height correction.—This is a correction for the increase of gravity with decrease of height for points outside the earth.

Let h = the height of the station above sea level.
g = observed gravity at h.
dg_1 = the correction due to change of height in reducing g to sea level.
R = the mean radius of the earth.
M = the mass of the earth.
K = the gravitational constant.
g_o = the reduced value of gravity = $g+dg_1$

Assume the earth to be a sphere, then,

$$g_0 = \frac{KM}{R^2}$$

$$g = \frac{KM}{(R+h)^2}$$

$$\therefore \quad g_0 = g\left(1 + \frac{2h}{R} + \frac{h^2}{R^2}\right).$$

Since h is very small compared with R the term h^2/R^2 may be dropped.

$$g_0 = g + dg_1 = g + \frac{2gh}{R},$$

$$\therefore \quad dg_1 = \frac{2gh}{R}.$$

It is a near enough approximation to consider g as a constant, so that the height correction dg_1 is equal to a constant times the elevation h.

Corrections for topography.—There are two types of corrections for topography. One is a convenient first approximation, and the second is an elaborate computation for the attractive effect of the topography of the entire earth, the density deficiency of the sea water being included. The approximate correction is derived by considering the topography about the station to be an infinite horizontal stone plate of uniform density, equal to the mean surface density of the earth, and of thickness equal to the elevation of the station. It can be shown that the attraction on a unit mass at a point outside due to such a plate is,

$$dg_2 = -2\pi k\delta h, \qquad (14)^1$$

where dg_2 is the correction to gravity g due to the attraction of the stone plate, K the gravitational constant, δ the density, and h the thickness (elevation of the station).

[1] A number of formulas similar to (14) have been stated without proof. These are all well-known physical formulas whose proofs are to be found in works on Newtonian Potential. It has, therefore, seemed inadvisable to break the line of thought by stopping to re-prove them here.

It happens, of course, that the surface of the earth about a station is seldom a fair approximation to a horizontal plane. A further correction is usually applied as a supplement to (14) to take account of this irregularity. This correction, which is known as the orographic correction, is computed from topographic maps of the region about the station to a convenient distance from the station.

Letting dg_3 be the orographic correction, then dg_3 is always positive (i.e., as added to g), because the missing mass below the plane of the station has already been assumed to exist, and its effect subtracted from g in the stone plate correction. Thus it must now be added back again. Similarly the mass above the plane of the station attracts against gravity, hence its correction increases g by the amount of its attraction.

The stone plate correction combined with the orographic correction is admittedly only a very convenient first approximation to an accurate topographic correction. In the more elaborate work, however, detailed corrections for the effect at each station of the topography of the whole earth have been computed and applied.

Let dg_T be the correction due to the attraction of all the topography (the land above sea level and mass deficiency due to water in the ocean basin) of the earth.

Corrections for isostatic compensation.—If one assumes a complete state of isostasy to exist, then corrections may be applied for the density deficiency beneath the continents and excess beneath the ocean basins. As a first approximation which is analogous to the stone plate correction for the topography one may assume that the missing mass below sea level is a negative stone plate of mass equal to the stone plate of topography above sea level. Then the correction for this is equal and opposite in sign to that for the topographic stone plate. Thus

$$dg_4 = +2\pi K\delta h \tag{15}$$

where dg_4 is the correction to g due to the missing mass below the station.

More elaborate corrections for the effect at the station due to isostatic arrangement below sea level have been computed by the United States Coast and Geodetic Survey under Hayford and

Bowie,[1] and in Europe by Heiskanen.[2] These are detailed computations of the attractive effect at the station due to the density deficiencies and excesses of the whole earth according to the hypothesis used. The former adopted a modified form of the Pratt hypothesis; the latter tried both the Pratt and Airy hypotheses.

Let dg_I be this more elaborate isostatic correction.

The free-air reduction.—The free-air reduction consists only of the height correction. It can more properly be thought of as an approximate isostatic reduction for which the reduced value of gravity g_0 is,

$$g_0 = g + dg_1 + dg_2 + dg_4$$
$$= g + \frac{2gh}{R} - 2\pi K\delta h + 2\pi K\delta h ,$$
$$\therefore \quad g_0 = g + \frac{2gh}{R} , \tag{16}$$

The free-air anomaly Δg is

$$\Delta g_{\text{free-air}} = g_0 - \gamma . \tag{17}$$

The Bouguer reduction.—This correction consists of the height correction and of the stone plate and orographic corrections.

$$g_0'' = g + dg_1 + dg_2 + dg_3 ,$$

or,

$$g_0'' = g + \frac{2gh}{R} - 2\pi K\delta h + dg_3 . \tag{18}$$

where g_0'' is the value of gravity so reduced.

The Bouguer anomaly is,

$$\Delta g_{\text{Bouguer}} = g_0'' - \gamma . \tag{19}$$

[1] J. F. Hayford, and W. Bowie, "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," *U.S. Coast and Geodetic Surv., Special Publication No. 10* (1912).

[2] W. Heiskanen, "Untersuchungen über Schwerkraft und Isostasie," *Veröffentlichungen des Finnischen Geodäten Institutes, No. 4* (1924).

The Pratt-Hayford reduction.—This reduction consists of the height correction, the topographic correction, and the Pratt-Hayford correction for isostasy.

$$g_{P\text{-}H} = g + \frac{2gh}{R} + dg_T + dg_{I(P\text{-}H)} \,. \tag{20}$$

The Pratt-Hayford anomaly:

$$\Delta g_{P\text{-}H} = g_{P\text{-}H} - \gamma \,. \tag{21}$$

The Airy-Heiskanen reduction.—This is identical with the Pratt-Hayford reduction except that the isostatic correction is based upon the Airy hypothesis as modified by Heiskanen instead of upon the Pratt hypothesis.

$$g_{A\text{-}H} = g + \frac{2gh}{R} + dg_T + dg_{I(A\text{-}H)} \,. \tag{22}$$

The Airy-Heiskanen anomaly:

$$\Delta g_{A\text{-}H} = g_{A\text{-}H} - \gamma \,. \tag{23}$$

Results from gravity reductions.—If the underlying theory be correct, the criterion of gravity reductions should be the size of the anomalies yielded. That reduction, the sum of the squares of the anomalies of which is least, has been taken to be the best.

TABLE I[1]

	467 Stations Mean with Regard to Sign
Bouguer anomaly	−.038
Free-air anomaly	+.015
Pratt-Hayford (1912) isostatic anomaly	+.009

Table I is a comparison of the Bouguer, free-air, and Pratt-Hayford (1912) anomalies for 467 stations in the United States, Europe, Asia Minor, and Spitzbergen. It gives a good idea of the relative sizes of anomalies yielded by various methods of reduction. The mean of the Bouguer anomalies from a representative number of land stations is usually the largest anomaly of all and negative;

[1] W. Heiskanen, *op. cit.*; W. Bowie, "Investigations of Gravity and Isostasy," *U.S. Coast and Geodetic Surv., Special Publication No. 40* (1917).

the mean of the free-air anomalies is considerably smaller than the Bouguer and may be positive or negative; while the mean of the more elaborate isostatic anomaly is in general the smallest and either positive or negative. In the case of the oceans Meinesz[1] reports the mean of seventeen Atlantic "sea-level" anomalies to be +.025 and the mean of fourteen such Pacific anomalies to be +.038. His tentative results gave even larger positive values for the isostatic anomalies.

Table II shows the relation between the sizes of the Bouguer and the Pratt-Hayford anomalies as a function of the elevations of the

TABLE II[2]

Elevation in Meters	Number of Stations	Non-algebraic Means of Bouguer Anomalies	Algebraic Means of Bouguer Anomalies	Non-algebraic Means of Pratt-Hayford (1912) Isostatic Anomalies	Algebraic Means of P.-H. (1912) Isostatic Anomalies
0–400.....	213	.027	−.010	.022	−.010
401–800.....	32	.039	−.037	.018	+.011
801–1,200.....	16	.104	−.104	.022	−.004
1,201–1,600.....	15	.128	−.128	.022	+.010
Over 1,600.....	20	.184	−.184	.014	+.003

stations. These data for the Bouguer when plotted graphically (Fig. 3) show that this anomaly is roughly proportional to the elevation of the station and is approximately equal to the stone plate correction, which is also proportional to the elevation.

Upon such as the foregoing data is the theory of isostasy founded. The vertical has been found to be deflected *less* than the attractive effect of the topography would lead one to expect. The value of gravity reduced to sea level has been found to be *greater* for oceanic stations and *less* for continental stations than was expected from a consideration of the attractive effect of the topography alone. The solution in both cases has involved an assumption of less than normal density beneath the protuberances and greater than normal density beneath the depressions of the lithosphere.

So monotonously consistent have been the qualitative results thus

[1] Vening Meinesz, "Gravity Survey by Submarine via Panama to Java," *Geog. Jour.*, Vol. LXXI (1928), pp. 151.

[2] William Bowie. *Isostasy* (1927), p. 77.

obtained that some of the leaders in favor of the isostatic theory have grown unduly bold. It has come to be the custom of W. Bowie,[1] for instance, to assert that isostasy is a condition of the earth's crust which has been proved by geodetic means to exist, and then to proceed to draw conclusions contrary to very obvious geologic data.

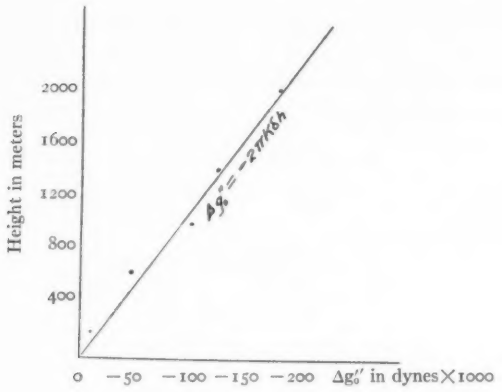

FIG. 3. Graph made from the data of Table II showing that the Bouguer anomaly is proportional to the elevation and negative. The anomaly is approximately equal to the stone plate correction.

THE WORK OF F. HOPFNER[2]

Not unlike a voice crying in the wilderness has been a series of recent papers by F. Hopfner. Hopfner has gone back to the fundamentals of potential theory to determine which methods of attack on problems pertaining to the geoid are justified by strict theory and which are not. He insists that only those methods are valid that are based upon directly observable data and involve no assumptions of the mass distribution below the geoid surface. In accordance with this view he has outlined a hypothesis-free method of determining

[1] W. Bowie, *Isostasy* (1927), p. 1. See also "Zones of Weakness in the Earth's Crust," *Science*, Vol. LXX (December 20, 1929); and "Elements of Isostasy, Observation, and Interpretation," *Scientific Monthly*, August, 1930, p. 163.

[2] F. Hopfner, a series of articles appearing in *Gerland's Beiträge zur Geophysik*, Vols. XIX–XXV (1928–30), inclusive.

the shape of the geoid from gravity data taken all over the earth. After the shape of the geoid with respect to a general spheroid of reference is known there will then be time enough to speculate upon such second order quantities as the superficial mass distribution within, but until that time these quantities must be considered as totally unknown.

Hopfner calls attention to the fact that the geoid is defined merely as a particular equipotential surface of the earth and that there is nothing inherent in such definition about its shape. Geometrical measurements such as triangulation cover only a small percentage of the area of the earth and tell nothing about the geoid outside the areas they represent. He points out the fact that the spheroid constants determined by triangulation of different regions have been appreciably different and that there is every reason to suppose that a different curvature in the geoid is in good part responsible for this difference. Triangulation does not tell whether the spheroid that best fits the geoid in a certain area comes nearer than a few kilometers to the geoid in remote points of the earth from that area. Considerable emphasis has been placed by geodesists upon the small deviations of the geoid from the spheroid. Hayford[1] found for the United States a maximum amplitude of deviation of the geoid with respect to the spheroid of 38 meters.

Here, as elsewhere, the really important consideration is that if the area of the geoid to be fitted with a spheroid be taken small enough an almost exact fit will result and there will be no deviation whatsoever between the geoid and the spheroid within that area. On the contrary, if the whole surface of the earth could be covered by one continuous triangulation net, the maximum deviations would certainly be greater than any thus far observed from measurements of small areas, and, as Hopfner states, they may equally well be 1,000 as 100 meters.

Since triangulation over any but limited areas is impossible the determination of the geoid with respect to a universal spheroid becomes a purely physical problem; the solution of which is to be sought in accordance with the laws of strict potential theory. The

[1] John F. Hayford, "Figure of the Earth and Isostasy from Measurements in the United States," *U.S. Coast and Geodetic Surv.* (1909).

only universally applicable method of attack at present available is by means of gravity measurements in conjunction with the laws of Clairaut and of Stokes.[1] This solution to be entirely valid must be executed without any assumptions concerning the mass distribution inside the geoid.

The level-spheroid.—Hopfner has adopted as a world-wide spheroid of reference what he calls the level-spheroid. Let $W = U_0$ be the value of the potential of the geoid. Then imagine the earth to be an ideal body such as is postulated for the Clairaut theorem. Let U be the potential of this ideal body. Then the equipotential surface $U = U_0$ is the level-spheroid. The distance from the geoid to this level-spheroid at every point is an unknown quantity which is to be determined by gravitational means. Only when this quantity is known for all parts of the earth is the shape of the geoid determined. There is at present no reason for supposing that this deviation may not exceed 1,000 meters or more over considerable areas.

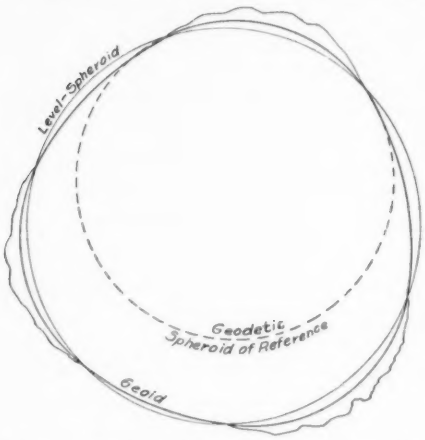

FIG. 4. Exaggerated diagram of a cross-section through the center of the earth showing the relation between the geoid, the level-spheroid, and the geodetically determined spheroid of reference. The geodetic spheroid of reference is made to fit a small part of the geoid but there is no data on how badly it misfits the rest.

Prey gravity reduction.—Hopfner next considers what kind of gravity reduction is permissible by strict potential theory. The desired quantity is the value of gravity at the geoid surface that would be obtained if one could actually set up his apparatus there and measure gravity without changing the earth by doing so. Since

[1] G. G. Stokes, "On the Variation of Gravity at the Surface of the Earth," *Mathematical and Physical Papers, No. 11* (1883), pp. 131–71.

on the continents this value cannot be measured directly it must be obtained indirectly from measurements at the land surface. The method of doing this is given by Prey[1] as follows: (1) measure gravity at the surface of the continent; (2) imagine next that continent outside the geoid is moved to an infinite distance away from the station; (3) then lower the station to the geoid; (4) replace the continent; (5) compute the correction to g for each of the above operations and the value at the geoid will be the result.

Let g = the observed value of gravity on the land.
h = the elevation of the station above sea level.
g' = the value of gravity on the geoid immediately below the station.
R = the mean radius of the earth.
b = the attraction of the continent at the point of observation.
b' = the attraction of the continent at the corresponding point on the geoid.

$$g' = g + \frac{2gh}{R} - b - b'. \tag{24}$$

In most cases b' is approximately equal to b which is, in turn, approximately the stone plate plus the orographic correction. Hence,

$$g' = g + \frac{2gh}{R} - 2b. \tag{25}$$

The objection to any of the other commonly used methods of reduction is that they are indissolubly confused with assumptions of isostasy and do not give the value of gravity on the geoid. The isostatic reductions amount essentially to condensing the mass above the geoid to make it cancel the assumed mass deficiency below sea level and computing the gravity at sea level as that of a point external to all this mass. The point on the geoid is actually an internal point for which the treatment must be quite different from that of an external point.

Bruns's term.—Hopfner has shown further that the value of gravity on the geoid is still not directly comparable to theoretical

[1] *Op. cit.*, p. 133.

gravity in the usual manner because the geoid and the level-spheroid do not in general coincide and may in most cases be a considerable distance apart.

Let N = the height of the geoid *above* the spheroid.

γ = the theoretical value of gravity on the level-spheroid.

g' = the value of gravity on the geoid.

Then a height correction for the height N must be applied to γ before the usual comparison can be made. Let γ' be the theoretical value of gravity on the geoid. Then,

$$\gamma' = \gamma - \frac{2\gamma N}{R},$$

$$g' - \gamma' = g' - \gamma + \frac{2\gamma N}{R},$$

$$g' - \gamma = -\frac{2\gamma N}{R}. \tag{26}$$

Hopfner refers to the expression $g' - \gamma$ as the true anomaly and the term $2\gamma N/R$ he calls Bruns's term because it was Heinrich Bruns[1] who first called attention to its importance. Equation (26) states

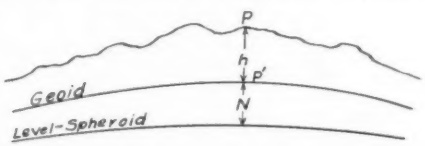

Fig. 5. The relation between the geoid and the level spheroid under a continent. Observed gravity at P must be reduced to P' and theoretical gravity γ must be "raised" to P' before the usual comparison can be made.

that the desired agreement between theoretical and observed gravity $g' - \gamma$ should not equal zero but should equal the quantity $-2\gamma N/R$ instead. If the earth had its present topography and if its outer shells were of constant density, then isostatic balance would be totally lacking, and the geoid would be above the spheroid under the continents due to their attraction and over the oceans it would be below the spheroid. Then $g' - \gamma$ should be negative

[1] Heinrich Bruns, *Figur der Erde* (Berlin, 1878).

over the geoid under the continents and should be positive over the oceans, because N would be positive for the continents and negative for the oceans.

By the Bouguer reduction,

$$g_0'' = g + \frac{2gh}{R} - b,$$

while by the Prey reduction,

$$g' = g + \frac{2gh}{R} - 2b.$$

or

$$g' = g_0'' - b.$$

It has already been seen that the Bouguer anomaly is equal approximately to $-b$. Hence the true anomaly will be,

$$g' - \gamma = g_0'' - \gamma - b = -2b = -\frac{2\gamma N}{R}. \qquad (27)$$

This immediately removes one of the main supports for the theory of isostasy. Isostasy was created to explain the fact that gravity appeared to be too small over the continents and too great over the oceans; now by a more careful consideration of underlying theory it is seen that the same gravity distribution could have been predicted by assuming no isostasy.

In a similar manner the deflections of the vertical depend upon the undulations of the geoid with respect to this level-spheroid. When these undulations are known, then, and not until then, will anything be definitely known about the magnitudes of the deflections. They certainly will be greater than those now obtained by fitting spheroids to small areas of the geoid.

These results of Hopfner are admittedly qualitative but they are of sufficient importance to cast a large shadow of doubt over the whole of isostatic theory. Hopfner[1] has shown how a general determination of the undulations of the geoid may be executed from

[1] F. Hopfner, "Die Hypothesenfreie Reduction und numerische Verarbeitung der beobachteten Schwerkraftwerte," *Gerland's Beiträge zur Geophysik*, Vol. XXV (1930), pp. 339–47.

gravity data by "hypothesis-free" methods. Until such hypothesis-free determination of the shape of the geoid shall have been executed it will be, perhaps, the better part of wisdom to be slightly sceptical of such sweeping statements as, "Isostasy is a condition of the earth's crust which has been proven by geodetic means to exist." The possible error of this statement may account for the fact that geological conclusions based upon it as a major premise have been known to be greatly erroneous.

SEISMOLOGICAL DATA

Seismological data give the results that the earth from its surface to about half way to its center is highly rigid to short-period stresses. Waves transmitted through the earth at depths greater than the outer 100 kilometers or so, require the same time for the same distance for all parts of the earth. This indicates that below a superficial layer the earth is approximately homogeneous in concentric shells with respect to physical properties. Near the surface there is more heterogeneity and there is a suggestion of abrupt changes of physical properties with depth at certain surfaces of discontinuity. There is nothing about this that has any particular bearing upon the theory of isostasy one way or the other.

GEOLOGICAL DATA

Geological data are too complex to be reviewed in detail here and too well known by geologists in general to require such a review. Diastrophism is the geologic process most concerned with theories of isostasy. Diastrophism consists mostly of movements of the lithosphere of two kinds: (1) the more or less vertical warps, both up and down, and (2) the folding and faulting of the lithosphere in mountain making involving horizontal movements often measurable in tens of miles. This last can have occurred only as a relief to stresses having a great horizontal component. There are a number of cases where the vertical movement seems to correlate very well with loading and unloading, but there are many others where such movement is known to have been independent of, or contrary to, the loading.

The energy involved in diastrophic events is probably derived mostly from the adjustment of the mass of the earth under the

influence of the earth's gravitational field. This adjustment is always toward a state of more stable equilibrium and may be said to be, on a more or less continental scale, an isostatic adjustment. Geological studies in general indicate that the correlation of uplift with unloading and of subsidence with loading postulated by the precise theories of isostasy is more often nonexistent than not.

SUMMARY

The fields providing data on the subject of isostasy are geodesy, seismology, and geology. The data of the first, which until recently have provided the main support of the isostatic theory, have been shown by Hopfner to be invalid. The data of the second have only an indirect bearing upon the question. The data of the last are more often than not contrary to isostatic expectations. Hence the theory of isostasy must, for the present, be regarded as resting upon a none too secure foundation and is hardly trustworthy for use as a major premise in present discussions of earth problems.

A TEXTURAL AND PETROGRAPHIC STUDY OF THE CAMBRIAN SANDSTONES OF MINNESOTA[1]

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Ohio State University

ABSTRACT

This study of the St. Croixan standstones was made to devise methods, other than paleontological, for correlating these formations. The variations in texture, shape, inclusions, and minerals are found to be as great in a single formation as they are in the different formations studied. Suggestive correlations can be made on the abundance of certain heavy mineral grains in definite grade sizes.

INTRODUCTION

Correlation of the Upper Cambrian formations of Minnesota has been made largely on paleontological grounds or on the broad lithologic characteristics of the rocks. Relatively little emphasis has been given to textural and microscopic studies of these sediments. At many localities there are few fossils; and where this is the case, it is often difficult to determine with certainty the exact stratigraphic position of the outcrop. The lithologic characteristics of the formations vary so greatly in a few miles that one formation may be mistaken for another if fossils are not found.

In the present study the connection of the stratigraphic units is attempted by the distribution of the various sizes of sand grains found, by the presence or absence of certain heavy minerals, by the mineral content of the samples, by the mineral inclusions, and by the shapes of the individual grains.

REGIONAL GEOLOGY

The region under investigation is in the southeastern part of Minnesota and the southwestern part of Wisconsin, as shown in Figure 1. In this portion of Minnesota the oldest outcropping rocks of Paleozoic age are the Dresbach sandstones and shales. The Dresbach varies in thickness from 200 to over 400 feet and is composed of

[1] The writer wishes to express his appreciation to Dr. F. F. Grout, Dr. W. H. Emmons, Dr. C. R. Stauffer, and Dr. A. C. Trowbridge for helpful advice and criticism during the preparation of this paper.

blue and green shales and sandstone with thin dolomitic layers. The variation is probably caused either by deposition on an irregular erosional surface or by uncertainty in determining the top and bottom of the formation. On the Wisconsin side of the Mississippi River a part of these sandstones has been called Eau Claire. In Wisconsin two formations, the Mount Simon and Eau Claire, are reported below the Dresbach and have an average thickness of a little over 1,100 feet. The description of the Eau Claire agrees closely with that of the Dresbach blue and green shales and sandstones found in Minnesota, with which formation it is now correlated.[1]

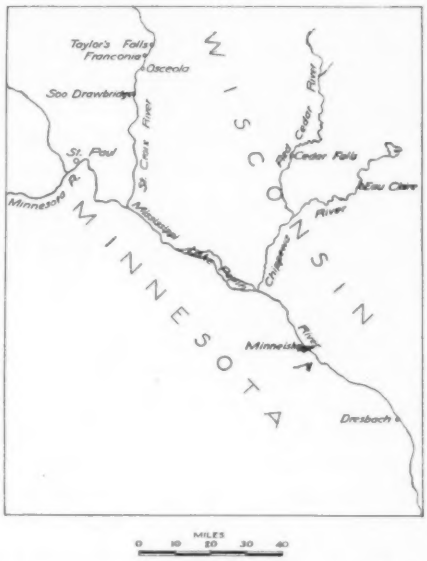

FIG. 1.—Outline map showing geographic distribution of samples.

Berkey, in 1897, gave the name Franconia to the top beds of the formation which the earlier writers had been calling Dresbach.[2] The Franconia sandstone is a rather thick-bedded, fine-grained, friable quartz sandstone, varying locally from white to brown or buff in color. Glauconite is sometimes found concentrated toward the top and bottom of the formation. In the basal part of the formation at the type locality there is a 2-foot conglomerate zone where large quartz pebbles are scattered irregularly through the coarse sandstone. The top of the formation is frequently marked by a flat

[1] Eunice Peterson, "The Dresbach Formation of Minnesota," *Bull. of the Buffalo Society of Natural Sciences*, Vol. XIV, No. 2 (1929), p. 42.

[2] C. P. Berkey, "Geology of the St. Croix Dalles," *Amer. Geol.*, Vol. XXI (1897), pp. 140–41.

pebble conglomerate. The thickness is from 50 to 80 feet in Minnesota, but twice this thickness is reported in Wisconsin.

The St. Lawrence is a thin-bedded series of buff magnesian limestones with alternating layers of more or less sandy green shales. A flat pebble conglomerate is often found marking the base of the formation in Wisconsin; and in Sand Creek at Jordan, Minnesota, a flat pebble conglomerate several feet thick marks the contact with the Jordan. The sandy shales are most abundant in the lower part of the formation, and the main dolomitic layers toward the top. The St. Lawrence commonly ranges between 100 and 200 feet in thickness.

The Jordan sandstone is a massive, friable, white to buff to brown sandstone. It contains distinctly cross-bedded layers especially prominent near the top of the formation. Thin lenses of green clay, some of which contain fossils, are often present in the upper portion of the formation. The thickness varies from place to place, ranging from 50 to 200 feet.

The Minnesota classification is essentially that proposed by Berkey in 1897. Owing to the nature of origin of this series,[1] considerable variation is found between two exposures of the same formation. This makes it inadvisable to carry over in Minnesota a number of minor divisions recognized in the Wisconsin section.

METHODS OF INVESTIGATION

FIELD STUDY

The locations showing the most complete sections in Minnesota and Wisconsin were chosen for detailed study. Samples of the rocks were taken at each exposure at vertical intervals of from 4 to 6 feet. Where unusual features were displayed, the distances between samples were varied accordingly.

LABORATORY STUDY

The laboratory study consisted of three parts: (1) the wet and dry preparation of the sample, (2) the textural determinations, and (3) the microscopic study. The procedure as described by Wentworth[2] was used in making the mechanical analyses.

[1] *Ibid.*, pp. 140–41.

[2] C. K. Wentworth, "Methods of Mechanical Analysis of Sediments," *University of Iowa, Studies in Natural History*, Vol. XI, No. 11 (1926).

Each separate obtained in the mechanical analysis of a given sample and the carbonate content of that sample is represented by the blocks of Figure 2. The material represented by each block is designated by various numbers and fractions. The term "grade," or "grade size," is used to designate the material caught on any given sieve, viz., the grains which pass through the $\frac{1}{2}$ mm. sieve and not through the $\frac{1}{4}$ mm. sieve constitute the $\frac{1}{4}$ mm. grade or grade size. The composite diagram representing all the separates of a given sample is the grade-size distribution of the sample.

ANALYSIS OF TEXTURAL DETERMINATIONS

GRADE-SIZE DISTRIBUTION

The grade-size distribution of the separates in each sample usually shows the development of the maximum percentage in one of the coarser grades, Figure 2. This maximum is often marked by an abrupt drop in the percentage of the material in the grades on either side. In only a few cases is there a secondary maximum present. The grade-size distribution found in each formation shows great lateral as well as vertical variation. This is shown in Figure 2.

Many of the detailed analyses made have been omitted from the figure. Their inclusion would have added little except to reinforce the conclusions drawn from those given. Some unusual features are greatly accentuated by the absence of many of the analyses made. All samples studied in detail, although not shown in the figure, are included in the discussion.

The Eau Claire sandstone is recognized only in Wisconsin, where it is a medium to very fine sandstone with varying amounts of silt and clay. Minnesota geologists consider the Eau Claire to be equivalent, at least in part, to the Dresbach of Minnesota. The contact between the Eau Claire and Dresbach was not observed in the present investigation.

The analyses of the samples from the type locality of this formation shows a definite tendency for the coarser grades to become more abundant toward the bottom of the section. In the section from Cedar Falls this formation shows the coarser grades toward the top. A detailed comparison of the analyses from the two sections shows only one case of approximate similarity, and this is not considered close enough to warrant correlation.

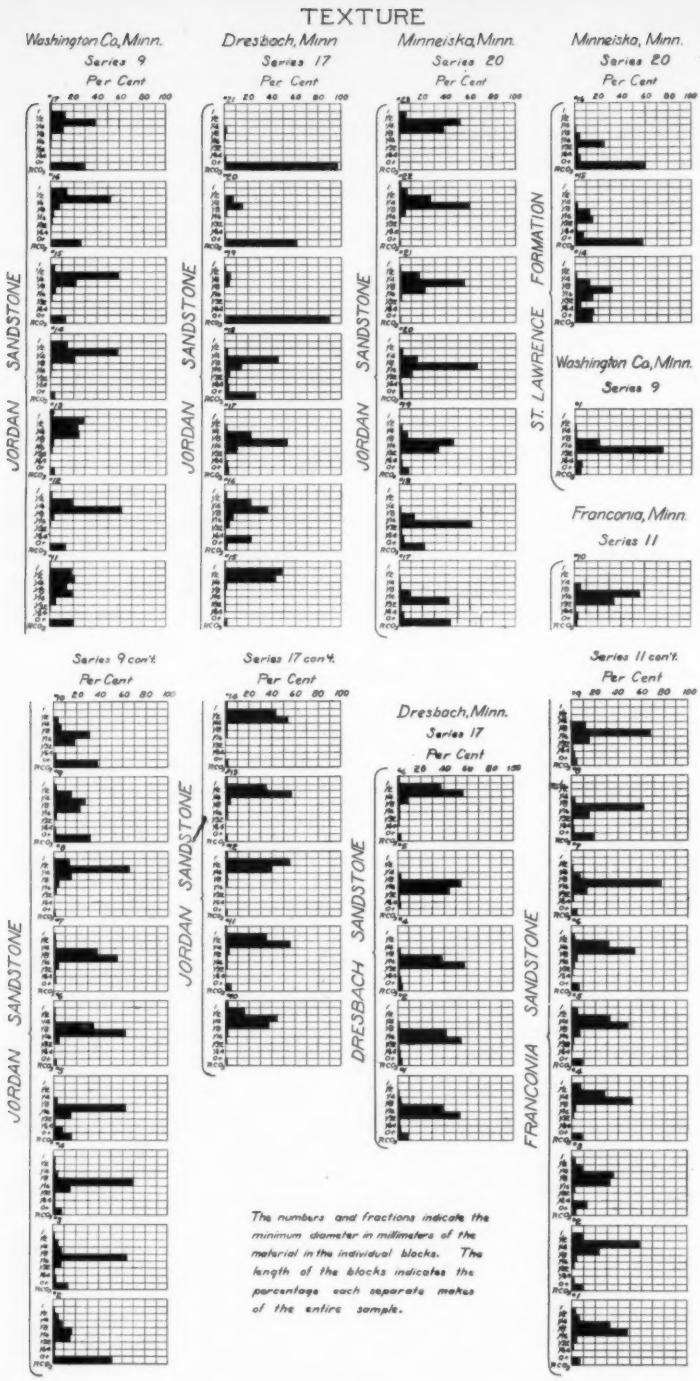
TEXTURE
Washington Co, Minn.
Series 9
Per Cent
Dresbach, Minn
Series 17
Per Cent
Minneiska, Minn.
Series 20
Per Cent
Minneiska, Minn.
Series 20
Per Cent
JORDAN SANDSTONE
JORDAN SANDSTONE
JORDAN SANDSTONE
ST. LAWRENCE FORMATION
Washington Co, Minn.
Series 9
Franconia, Minn.
Series 11
Series 9 con't.
Per Cent
Series 17 con't.
Per Cent
Dresbach, Minn.
Series 17
Per Cent
Series 11 con't.
Per Cent
JORDAN SANDSTONE
JORDAN SANDSTONE
DRESBACH SANDSTONE
FRANCONIA SANDSTONE
The numbers and fractions indicate the minimum diameter in millimeters of the material in the individual blocks. The length of the blocks indicates the percentage each separate makes of the entire sample.

FIG. 2

The analyses of the Eau Claire from its type locality are strikingly similar to those of the Dresbach in the high degree of sorting and the sizes of the constituent grains. But it is not thought that correlation can safely be made between formations on such generalized similarities; they are merely suggestive. The analyses of the Eau Claire from Cedar Falls, Wisconsin, do not indicate quite so high a degree of sorting as is found in the type section of this formation. This condition suggests that the circulation of the transporting waters to the open sea was at times partially blocked, with the resultant loss of transporting competency of the streams or currents. The formation is of shallow-water marine origin, as shown by its fossils and ripple marks.

The Dresbach sandstone is represented in two series, one from the type locality. This sandstone is composed of a medium to very fine sandstone with varying amounts of silt and carbonate. The texture varies from one locality to another.

The analyses are not similar in detail in the various sections studied, except in one case, and even there the similarity is not great enough for anything more than a suggested correlation. The mechanical analyses are not of value in correlating this formation.

The Dresbach sandstone shows a greater degree of sorting than is found in either the Jordan or Franconia sandstones. In general, the texture is finer than that of the Jordan and about the same as that of the Franconia. In most of the analyses 90 per cent or more of the total material of the sample occurs in two grades, sometimes coarse and sometimes fine. The presence of marine fossils in considerable abundance at many localities indicates marine conditions below violent wave action, thus preventing the destruction of the frail shells by the attrition of the sands. The deposits, however, were not at all times below water, and clearly indicate exposure to the air with the consequent development of mud cracks. Ripple-marked layers also indicate the existence of shallow-water conditions. The carbonate content is variable, ranging from 0 per cent to nearly 90 per cent. Twenhofel and Thwaites[1] state that the Dresbach of the Tomah and Sparta quadrangles is an accumulation of sands on sand flats above wave base and in part out of water.

[1] W. H. Twenhofel and F. T. Thwaites, *Jour. Geol.*, Vol. XXVII (1919), p. 623.

The relationship between the Dresbach and Franconia is one of general conformity. No break in sedimentation is indicated in the analyses. At Franconia, Minnesota, a 2-foot zone of slightly conglomeratic sandstone occurs at the base of the Franconia. This is the only location where this conglomerate was observed.

The Franconia sandstone is made up of a series of fine to very fine sandstones with varying amounts of silt, clay, and carbonate. This is true of the formation everywhere it was examined. Series 11 is from the type locality of this formation and was chosen as the representative series (Fig. 2).

This formation clearly shows a tendency to develop very fine sandstones at the top with an increasing coarseness downward. There is a slight similarity among several analyses, but the differences are as great as those sometimes found between formations. It is not safe to correlate the Franconia on the basis of texture.

The Franconia is well sorted and very uniform in texture. The high degree of sorting indicates deposition under conditions similar to those of the Dresbach. The depth of the Franconia sea was not great. The presence of mud cracks in some of the shaly layers indicates drying and cracking of the sediments in air. Presumably the drying took place on tidal flats. Ripple marks have been noted in the Franconia of Wisconsin although they were not found in Minnesota.

The carbonate content of this formation is irregular and is not thought to be of any significance in determining a stratigraphic horizon or the conditions under which the sandstone was deposited.

The St. Lawrence formation shows a very erratic grade-size distribution. No two of the analyses are strikingly similar, although silt, clay, and carbonate make up the bulk of each sample. The formation becomes slightly finer toward the top, where the clastic material is composed of clay, silt, and very fine sand.

This formation is of finer texture than any of the other formations. The fine grades at the base of the Jordan and in the St. Lawrence indicate a continuous sequence of deposition with no marked transitional break between the formations. At the top and at the base of the St. Lawrence a flat pebble conglomerate is found. The conglomerate has flat sandstone pebbles like shingles, with the long

dimensions of the pebbles parallel to the bedding planes. This indicates a slight break in continuous deposition, a diastem, at the top and bottom of the formation.

The carbonate content is also less at the base of the formation. This indicates either lower temperature, less agitation and aëration of the water, more rapid erosion of the land, or a shoaling of the sea in which the sediments were accumulating. In general, it might be said that the St. Lawrence sea was shallow at the beginning, moderately shallow during the main part of the epoch, and again becoming shallow toward the close. It is clear, however, that oscillations of sea level occurred, since mud cracks are developed locally in some of the shaly layers. The flat pebble conglomerates suggest that the greatest breaks in conditions of sedimentation occurred at the top and bottom of the formation, although the mechanical analyses of the material near the conglomerate zones do not indicate distinct breaks.

The Jordan sandstone shows an exceedingly variable development in the grade-size distribution of each series. This feature is more strikingly displayed when several series are compared, as in Figure 2. There is a tendency for the formation to become coarser toward the top, although Series 17 shows the reverse. The lack of horizontal uniformity makes it difficult to correlate this formation on the basis of the grade-size distribution. However, when a sample is found showing a relatively high percentage of the $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{8}$ mm. grades, it might be suggested that it came from the upper rather than the lower part of the Jordan.

In many samples 80 per cent to 90 per cent of the material is found to be of two or three grades. The other grades, although present, are found in small amounts. This distribution suggests that the deposition of these sands took place in an open sea which allowed the bulk of the silt and clay particles to be carried farther from shore, or that the sands had previously been sorted. Some samples show a considerable amount of material of very fine grain mixed with an abundance of much coarser material, indicating the temporary existence of unusual conditions of deposition. This irregularity may have been caused by the development of (1) bars or other obstructions which prevented uninterrupted transportation of the fines to

deep water, (2) an increase in the rate of erosion causing the streams to carry greater loads to the sea, (3) the proximity to the source of the fine materials, or (4) greater flocculation of the fine materials near shore. Just which of the four conditions caused the irregularities cannot be stated.

The varying carbonate content of the samples is very evident in the textural-analysis diagrams, an irregularity not entirely due to conditions of deposition. In some of the specimens secondary carbonate was identified, especially in the Jordan sandstone, where large calcite crystals, many of them 2 inches or more in length, were found growing around the sand grains for some distance below the Oneota dolomite. This secondary carbonate causes an increase in carbonate content as the Jordan-Oneota contact is approached. Since the carbonate content is not all original carbonate, its value for purposes of correlation, or in giving a clear idea of the lime-depositing conditions of the Cambrian sea, is not great.

PETROGRAPHIC STUDY

Bromoform with a specific gravity of 2.8 was used to separate the heavy minerals in the samples, with the help of a Penfield separatory funnel equipped with a plunger and detachable cup. The heavy minerals were collected on a filter paper washed with alcohol and dried. They were then mounted in piperine (index of refraction, 1.68) for microscopic study in permanent slides. Any heavy minerals not mounted were saved for special study as occasion arose. If the heavy separate was small in amount, it was all used in making a single slide. The light minerals were also collected on a filter paper, washed, and saved for study. The microscopic study consisted of a determination of the minerals present in each heavy separate, their shape, size, color, inclusions, and secondary growth. The shapes of the light minerals determined are plotted in Figure 3. The characteristic shapes for each degree of rounding are shown in Figure 4.

LIGHT MINERALS

The light minerals make up more than 95 per cent of each sample. Quartz is present in amounts well over 90 per cent in all samples, except in a few highly glauconitic ones. The percentage of glauco-

nite is very variable, both laterally and vertically, in the same formation, making it a poor criterion for correlation.

Muscovite is common in many samples. It is very rarely found with a maximum diameter as great as $\frac{1}{4}$ mm. In different samples

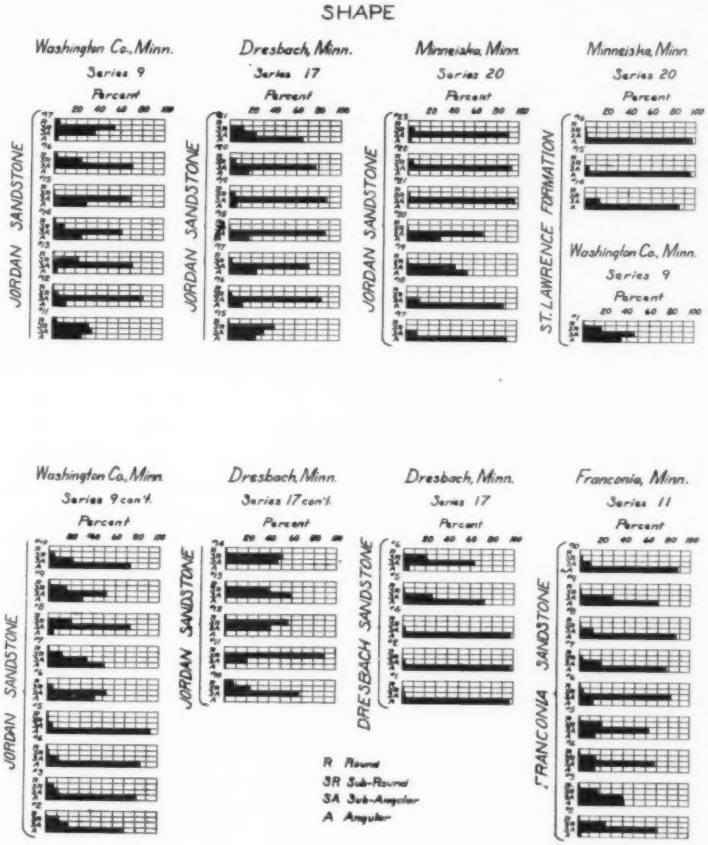

FIG. 3

this mineral is found to vary greatly, occasional fine separates having as much as 80 per cent muscovite. These fine separates make up a small percentage of the sample, so that the total percentage of

muscovite in the samples is seldom over 2 per cent. Some samples had a recognizable amount of muscovite smaller than 1/64 mm. This was lost with the clay and some silt during the preparation of the samples for study.

The feldspars orthoclase, microcline, and plagioclase occur in the same textural relations as the muscovite. Some of them occur as euhedral crystals among the angular grains in the finer grades, 1/32 and 1/64 mm., whereas in the $\frac{1}{8}$ and 1/16 mm. grades they show the effect of fracture and wear. See Figure 4, *E*. The percentage of feldspar in an entire sample is low; but in the 1/64 mm. separate it is consistently high, in many cases over 50 per cent. The feldspar is characteristic and uniform in the fine grades of all the formations studied, and hence is not a good diagnostic mineral in these formations.

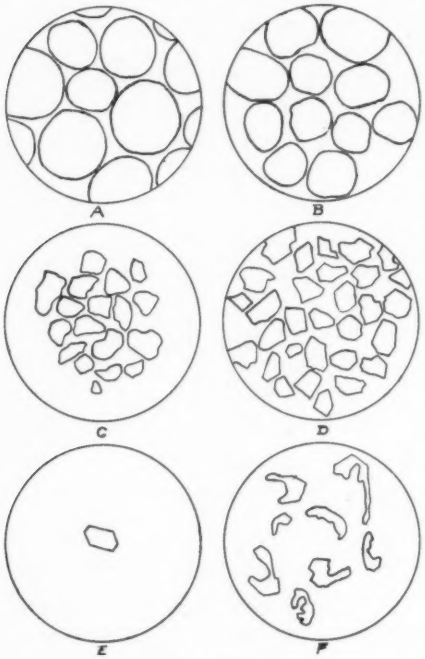

FIG. 4.—Tracings of microphotographs of: *A*, rounded grains; *B*, subrounded grains; *C*, subangular grains; *D*, angular grains; *E*, euhedral feldspar crystal; *F*, grain crusts.

The quartz in the coarser grades shows considerable wear, but in the 1/16 and 1/32 mm. grades it is angular to subangular. There are no differences in the quartz grains in the various formations.

INCLUSIONS IN THE LIGHT MINERALS

Quartz is the only mineral with a specific gravity less than 2.8 that has inclusions. The other minerals—muscovite, glauconite,

plagioclase, orthoclase, and microcline—are without any observed inclusions. See Figure 5.

The most common inclusion in the quartz is tourmaline. Many grains have several small inclusions, and in the bigger grains large inclusions are frequently found. The usual color of the tourmaline inclusions is olive green, although some deep-green colors were observed. In nearly every case these inclusions have the shape of a prism with rounding terminations. Inside some of the tourmaline inclusions unidentified inclusions were noted.

The apatite inclusions in the quartz grains vary considerably in size and shape, ranging from euhedral to anhedral crystals with well-rounding terminations predominating. In many of the larger quartz grains there are from three to five apatite inclusions of varying sizes. These inclusions are characteristically smaller than those of tourmaline.

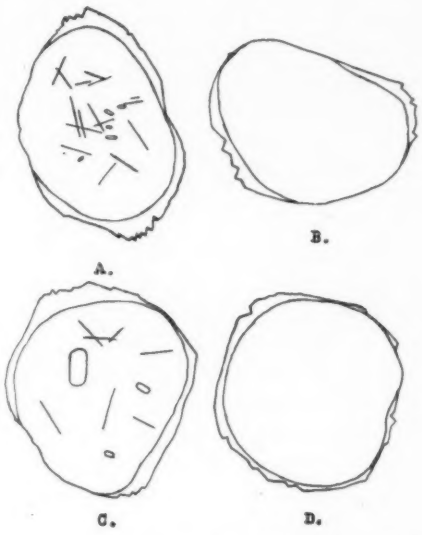

FIG. 5.—Secondary growth of quartz around worn sand grains. *A* shows inclusions of apatite and rutile needles; *C* shows inclusions of tourmaline and rutile needles. × 30. Camera-lucida drawings.

Inclusions of very thin rutile needles are quite common in the quartz grains. In both size and shape they are identical with those found in some of the heavy mineral grains.

Feldspar inclusions are present in the quartz grains but are not abundant. Plagioclase showing albite twinning is the only definitely identified feldspar. Orthoclase is also probably present.

Unidentified inclusions with indices less than quartz are fairly common in the quartz grains. In some cases the index is only slightly

lower than the quartz, suggesting orthoclase. In others, the index is still lower, and the shape is somewhat spherical, suggesting liquid and gas inclusions.

The inclusions in the light minerals cannot be used successfully as diagnostic criteria for any of the formations studied. The variations from formation to formation are no greater than the variations found in a single formation. Inclusions are found in all sizes of grains, from the largest down to, and including, those 1/32 mm. in diameter. Inclusions may be present in the grains 1/64 mm. in diameter, but were not observed.

This marked similarity in the inclusions of the light minerals suggests a common or similar source for the sediments in all the St. Croixan formations under investigation.

GRAIN SHAPES

The shape analysis of any given sample, compared with the textural analysis of the same sample, usually shows the following relationships: the grains that have minimum diameters less than ½ mm. are notably angular; the coarser grains have the higher degrees of rounding; the grains larger than 1/64 mm. and smaller than 1/32 mm. invariably are 100 per cent angular. Refer to Figures 2 and 3 for the relationship between texture and shape. See Figure 4, *A–D*.

Table I suggests a possible means of correlation. It is not thought, however, that the table will be of much service in this respect since the relationship of texture to shape is governed mainly by the predominant size of the grains in a given sample. Lack of sufficient wear in some few cases has left some coarse angular grains, for example, the 1 mm. grade in the Franconia. The textural variation of each formation is great, making it possible to match samples from one formation closely with samples from the other formations. This is shown in the analyses of Figures 2 and 3.

SECONDARY GROWTH

Secondary growth of the quartz grains is very evident in most of the samples studied. Crystal faces are numerous on grains as small as 1/16 mm. in diameter. The most striking case of secondary growth was observed in No. 15 of Series 17 from the Jordan sand-

stone, where grains 1 mm. in diameter show the development of both prism and pyramid faces. The original shape of many of the grains is still clearly visible, due to a coating of iron oxide over which the secondary quartz was deposited (see Fig. 5). In the smaller grades secondary growth is evidenced by prisms and doubly terminated pyramids rather than by well-developed single crystal faces characteristic of the coarser grains.

TABLE I

AVERAGE TEXTURE WITH REFERENCE TO AVERAGE GRAIN SHAPE FOUND IN THE FOUR ST. CROIXAN FORMATIONS

(The Total Amount of Material in Each Grade Was Calculated as 100 Per Cent)

MINIMUM DIAMETER OF GRAINS (MM.)	JORDAN SANDSTONE				FRANCONIA SANDSTONE			
	R	SR	SA	A	R	SR	SA	A
1	4.1	85.7	10.2	.....	16.6	61.1	0	22.3
1/2	3.7	53.9	42.3	0.07	2.6	37.7	58.9	0.8
1/4	0.04	26.1	70.1	3.7	0.2	21.8	73.2	4.8
1/8	0.05	10.4	78.4	11.2	0.1	13.1	72.8	14.0
1/16	.....	1.4	41.0	57.6	.....	0.6	22.1	77.3
1/32	.....	0.05	16.0	84.0	.....	0.2	7.3	92.5
1/64	.....	.....	.....	100.0	.....	.....	.....	100.0
	ST. LAWRENCE FORMATION				DRESBACH SANDSTONE			
1	.....	.....	.....	.....	.....	.....	.....	.....
1/2	20.0	70.0	7.0	3.0	.....	49.0	48.5	2.5
1/4	1.7	22.9	67.4	8.0	.....	13.4	83.4	3.2
1/8	0.08	20.9	51.2	27.8	.....	5.0	80.2	14.8
1/16	.....	4.5	16.4	79.1	.....	.....	8.0	92.0
1/32	.....	4.0	12.5	83.5	.....	.....	8.8	91.2
1/64	.....	.....	.....	100.0	.....	.....	.....	100.0

Anatase in all cases occurs in tabular euhedral crystals and is the only heavy mineral showing any evidence of secondary growth. It has been suggested that ilmenite, on weathering, may form anatase. None of the anatase grains observed were attached to altering ilmenite grains, but were found as tabular euhedral crystals, some of them twinned.

SOLUTION EFFECTS

Since the original deposition of these formations some solution has taken place. Occasional grain crusts are found with hollow, more or less shapeless interiors, suggesting secondary growth of quartz

prisms and pyramids. This indicates solution of the original grain after deposition of the secondary quartz. These crusts are illustrated in Figure 4, *F*. This is the only feature found that indicates solution of any of the grains in these formations. It is best developed in the fine grades, especially in the 1/64 mm. grade. Such crusts are found in all formations.

TABLE II

DISTRIBUTION OF THE HEAVY MINERALS* IN EACH FORMATION, BASED ON MINERAL VARIETY AND TEXTURE
(Count Made on 100 Heavy Mineral Grains from Each Formation)

GRADE-SIZE (MM.)	G	T	Z	R	Br	Au	An	M	Bi
	JORDAN SANDSTONE								
1/4 –0.250	R	VR							
1/8 –0.125	VC	R	VR						
1/16–0.062	A	VA	VC	VR	.....	R	.....	.....	VR
1/32–0.031	VA	VC	VA	VC	R	R	VR		
	ST. LAWRENCE FORMATION								
1/4 –0.250									
1/8 –0.125									
1/16–0.062	VA	VA	R						
1/32–0.031	VA	VC	VA	VC	C	.....	VA	VR	
	FRANCONIA SANDSTONE								
1/4 –0.250									
1/8 –0.125	R	C	VR	.....	.....	.....	VR		
1/16–0.062	A	VA	A	.....	.....	.....	VA		
1/32–0.031	VA	VC	VA	C	.....	.....	R		
	DRESBACH SANDSTONE								
1/4 –0.250	VR								
1/8 –0.125	C	VR	VR						
1/16–0.062	VC	VA	VC	VR	.....	.....	VC	.....	VR
1/32–0.031	VA	VC	VA	VC	.....	.....	C		

* G = garnet, T = tourmaline, Z = zircon, R = rutile, Br = brookite, Au = augite, An = anatase, M = monazite, Bi = biotite. VR = very rare, 1–2 grains; R = rare, 3–4 grains; C = common, 5–6 grains; VC = very common, 7–8 grains; A = abundant, 9–10 grains; VA = very abundant, 11 or more grains.

GRADE-SIZE DISTRIBUTION OF THE HEAVY MINERALS

The heavy minerals are found distributed through the $\frac{1}{4}$, $\frac{1}{8}$, 1/16, and 1/32 millimeter grades; see Table II. The difficulty with this method of correlation is that individual samples from a single formation contain varying percentages of the different heavy minerals,

making it necessary to study a number of samples from a formation before attempting to locate the formation stratigraphically.

Table II shows the following relationships between texture and abundance of the various heavy minerals in each formation.

The Dresbach sandstone is suggested when: (1) garnet is very rare in the $\frac{1}{4}$ mm. grade, common in the $\frac{1}{8}$ mm. grade, and very common in the 1/16 mm. grade; (2) tourmaline is very rare in the $\frac{1}{8}$ mm. grade; (3) anatase is very common in the 1/16 mm. grade and common in the 1/32 mm. grade.

The Franconia sandstone is suggested when: (1) garnet is rare in the $\frac{1}{8}$ mm. grade; (2) tourmaline is common in the $\frac{1}{8}$ mm. grade; (3) zircon is very rare in the $\frac{1}{8}$ mm. grade; (4) rutile is common in the 1/32 mm. grade; (5) anatase is very rare in the $\frac{1}{8}$ mm. grade, very abundant in the 1/16 mm. grade, and rare in the 1/32 mm. grade.

The St. Lawrence formation is suggested when: (1) no heavy minerals as large as $\frac{1}{8}$ mm. are found; (2) garnet is very abundant in the 1/16 mm. grade; (3) zircon is rare in the 1/16 mm. grade; (4) anatase is very abundant in the 1/32 mm. grade.

The Jordan sandstone is suggested when: (1) garnet is rare in the $\frac{1}{4}$ mm. grade and very common in the $\frac{1}{8}$ mm. grade; (2) tourmaline is very rare in the $\frac{1}{4}$ mm. grade and rare in the $\frac{1}{8}$ mm. grade; (3) augite is rare in the 1/16 mm. grade and also in the 1/32 mm. grade; (4) anatase is very rare in the 1/32 mm. grade.

FORMATIONAL DISTRIBUTION OF HEAVY MINERALS

In the Dresbach the heavy minerals are very irregular in amount, garnet and zircon being the only minerals present in every sample. Rutile in one sample not shown in the analyses reached the highest content observed in any formation, 12 per cent of the heavy separate.

The heavy minerals in the Franconia are variable. The garnet content is nowhere greater than 60 per cent. Similar amounts are found in all of the other formations. Both zircon and tourmaline are abundant minerals but show no distinctive features of occurrence. Rutile is no more significant than the other minerals; but anatase, when present in the heavy-mineral separates in amounts over 20 per cent, is suggestive of this formation.

The heavy-mineral analyses of the St. Lawrence show similarities

which might be usable in correlation. The presence of brookite in nearly all samples is characteristic of the St. Lawrence, although occasional samples from other formations contain this mineral. When brookite is persistently present, the St. Lawrence is suggested.

The distribution of heavy minerals in the Jordan is highly variable, a single section showing contrasts as great as those in the different formations. The individual exposures of the Jordan show great differences in mineral proportions and occasionally the introduction of new minerals.

A comparison of the results of the heavy-mineral analyses makes it evident that these minerals are very erratic in their development and of little significance in correlation. Some minerals suggest possible correlations, but it is not believed that such correlations are always dependable.

The garnet forms a greater percentage of the heavy-mineral separates in the Jordan than in any other formation. However, some very marked exceptions reduce its value for correlation. If garnet occurs in the heavy separates in amounts greater than 90 per cent, it suggests the Jordan; but if present in smaller amounts, it might be from any one of the other formations.

Zircon is highly variable in all formations. The amount in the St. Lawrence, Franconia, and Dresbach formations, with but one exception, can be matched in one or more heavy-mineral analyses from the Jordan. In correlation, when 75 per cent or more of the heavy separate is zircon, the Franconia is suggested; but amounts less than 6 per cent suggest the Jordan.

Tourmaline is so variable as to be valueless for correlation, varying as much among the different sections of the same formation as it does among the different formations.

Rutile, found in small amounts in all formations, is present in its greatest amount in the Dresbach, where, in one sample not shown in Figure 6, it forms 12 per cent of the heavy mineral separate. It usually is subordinate, not exceeding 5 per cent of the heavy crop. When rutile is present in amounts greater than 10 per cent, the Dresbach is suggested.

Monozite and biotite are so rare that they are of no significance in correlation.

Anatase occurs in small amounts in all formations. It is not found in all samples from any one formation. In the Franconia it reaches 20 per cent of the heavy-mineral separate in one sample, which is

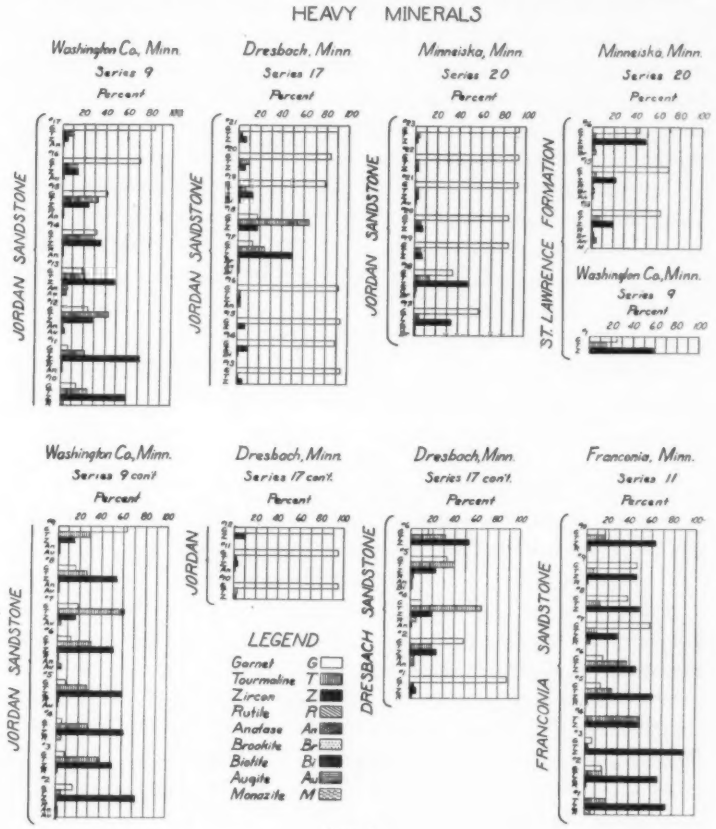

FIG. 6

the highest observed percentage. Amounts greater than 10 per cent of the heavy crop are suggestive of the Franconia.

Brookite, when consistently present in a series of samples, suggests the St. Lawrence formation, while its occurrence in occasional samples is of little significance in correlation.

Augite has no correlative value, since it was found in only one section of one formation, namely the Jordan. It never forms more than 5 per cent of the heavy-mineral separate.

The heavy minerals of the St. Croixan show a marked uniformity in all formations. The abundance of these minerals varies so greatly in some sections of the same formation that their use for correlation is merely suggestive. Several of the minerals are not present in all separates from a given formation, which makes the absence of a mineral from a particular sample of little significance.

The marked similarity in the heavy-mineral composition of the Cambrian formations suggests prolonged erosion of a rock series which was fairly uniform over a wide area. In localities showing unusual amounts of certain minerals the suggestion might be offered that (1) a change in the rate of erosion had occurred, or (2) the minerals were collected in a localized pocket where slight differences in specific gravity were important in sorting, or (3) local outcrops of distinctly different rocks were being eroded in definite drainage basins.

INCLUSIONS IN THE HEAVY MINERALS

The heavy minerals contain a variety of inclusions which cannot always be identified. Apatite, rutile, zircon, and several unknown inclusions were observed.

Tourmaline.—The tourmaline grains commonly showed large roundish inclusions appearing to be of the same color as the tourmaline, possibly because of the color of the tourmaline above and below the inclusion. If this is the true cause of the observed color, the real color of the inclusions may be light or colorless. The index of refraction is commonly higher than that of tourmaline, but in some cases is lower. Numerous hairlike prisms of rutile are present in some of the grains but are never as abundant as the previously mentioned inclusions. One grain of tourmaline contained an inclusion of zircon with a strong halo around it.

Garnet.—The inclusions in garnet are far less numerous than those in tourmaline. The garnet grains commonly had inclusions with indices both higher and lower than the index of the garnet. Many of the inclusions are anisotropic, but others are isotropic. In general, these grains have but three or four inclusions, although a few grains

were found with ten to fifteen inclusions. Apatite and very thin rutile needles are the only definitely determined inclusions found in garnet. The garnet grains from all formations had the same number, size, shape, mineral species, and associations of inclusions.

Zircon.—The zircon grains have fewer observed inclusions than any of the other heavy minerals, a scarcity apparently due to the fact that the high relief of the zircon prevents their detection. Although no inclusions were definitely determined, one had an index greater than zircon and may have been cassiterite.

None of the other heavy minerals showed inclusions.

It is not possible to distinguish any of the formations studied on the basis of the inclusions in the heavy minerals, because they are very similar in number, association, and mineral species in all formations.

SOURCE OF MATERIAL

The source of the material making up this series of rocks is probably the older rocks to the north. It does not seem likely that the erosion of igneous or metamorphic rocks of pre-Cambrian age during St. Croixan time has contributed more than a small part of the material. It is much more probable that the erosion of older sediments supplied most of the sands. This source for the sand is suggested by the marked degree of rounding shown by most of the grains and by the high degree of sorting found in the formations. The rocks of the St. Croixan were, beyond question, derived from igneous and metamorphic rocks at some earlier date; but it seems necessary that they pass through more than one erosion cycle before attaining their present degree of rounding and sorting.

CONCLUSIONS

1. Correlation of the four St. Croixan formations cannot be made on the basis of the grade-size distribution as found in the different formations.

2. Shape analyses of these sediments are of no value for correlation.

3. The light-mineral association, solution action, secondary growth, and inclusions are similar in the four formations.

4. It is not safe to use the percentages of the various heavy minerals from each formation, as recorded in Figure 5, for correlation in most cases, although certain tentative correlations may be made.

5. The inclusions in both light and heavy minerals are similar, which suggests a common origin and history for these mineral grains.

6. Suggestive correlations can be made on the basis of the grade-size distribution of the heavy minerals.

7. Heavy minerals are of greatest correlative value where the sediments of definite formations have been derived from the erosion of different rock types or where the sediments have been subjected to different degrees of wear.

8. Paleontologic evidence is the best means of determining the different formations of the Cambrian of the Upper Mississippi Valley.

9. The divisions of the Cambrian, in the area under investigation, are made on the basis of paleontology, and not on breaks or marked changes in sedimentation, with the exception of the diastems marked by the flat pebble conglomerates at the base and top of the St. Lawrence and top of the Jordan.

10. These deposits represent deposition in a subsiding marine area of accumulation with very slight breaks in sedimentation. At times this basin became locally filled with sediment, allowing the development of cross bedding, ripple marks, and mud cracks.

11. The conditions of sedimentation were, in general, similar over the entire area, the deposits being formed in shallow waters, allowing transportation of sands for long distances.

12. The high degree of sorting and rounding indicates the re-working of pre-existing sedimentary rocks or the extensive working and re-working of the sedimentary materials by wind, water, or waves, or by combinations of the three processes. The water sorting probably predominated.

A CORRELATION OF MARL BEDS WITH TYPES OF GLACIAL DEPOSITS[1]

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ABSTRACT

From a study of the distribution of bog marl in Minnesota, it is evident that some types of glacial deposits are more favorable for the development of marl than others. By ignoring all factors influencing the precipitation of calcium carbonate from lake waters and by taking into consideration the field relations only, as they now exist in regions where marl has accumulated, the following generalizations may be made:

1. The greatest number and also the largest deposits of marl are found in areas of coarse outwash sands and gravels.
2. In morainic areas, the sandy and stony moraines of the red drift contain a far greater number of marl deposits than the limy and clayey moraines of the young gray drift, even though the latter contains more lime.
3. Few marl deposits are found in lake basins, clayey till plains, or in areas of fine outwash sands.
4. Other conditions being favorable, high, irregular morainic topography favors the accumulation of marl.

INTRODUCTION

Most of the present physiographic features of Northeastern United States and Eastern Canada owe their origin directly or indirectly to the influence of glaciation. Within this area of approximately 4,000,000 square miles, conditions favorable for the accumulation of lacustrine marl have resulted from the unequal deposition of drift, which left the land dotted with thousands of glacial lakes. Many of these lake basins are filled with peat; others have almost disappeared because of stream erosion, while in many others, marl is slowly accumulating and the process may now be observed. Numerous deposits have been mapped in Indiana, Michigan, Wisconsin, and Minnesota.

From a study of the distribution of the marl beds in Minnesota, it is evident that some types of glacial sediments involve conditions more favorable for the accumulation of lacustrine lime beds than others. The object of this paper is to show the relation that exists

[1] Published by permission of the director of the Minnesota Geological Survey. Assistance in preparing this article has been received from the Research Fund of the Graduate School, University of Minnesota.

between the number and magnitude of marl deposits and characteristic glacial deposits such as hilly moraines, outwash plains, and till plains.

GENERAL CHARACTER OF GLACIAL LAKE MARLS

The term "marl" as used in this article is confined to the soft, earthy material, composed largely of calcium carbonate, that is found as a postglacial fresh-water deposit in lake basins, or bogs, and marshes that were once covered with water. It is usually grayish white or buff in color, but darker shades may be seen where the marl is contaminated with peaty organic material. The purer samples become white or slightly cream colored when thoroughly dried. The particles of which the marl is composed are mostly of very fine grain. In some deposits the shells of small snails and other molluscs are very abundant, whereas in others no traces of shells are found. The hardness and consistency of the fresh marl varies with the thickness of the bed, and with the degree of drying. In bogs that are partially drained, it is sufficiently firm to be cut into blocks or handled with a shovel. However, in lakes where deposition is still in progress, it occurs as a suspension of freshly precipitated $CaCO_3$ that is as easily agitated as a precipitate in a beaker in the laboratory.

SOURCE OF LIME

The source of the lime deposited as marl is the heterogeneous mass of clay, sand, gravel, and boulders which constitutes the glacial drift. By virtue of its mode of origin, this glacial débris contains an appreciable amount of fresh or chemically unaltered rock fragments. In some drift sheets, fragments and pebbles of limestone are abundant; in others, finely divided igneous or metamorphic rock-forming minerals, some of which contain lime compounds, constitute the major part of the drift. Meteoric waters percolating through such limy clays and gravels toward the glacial lake basins carry with them dissolved carbon dioxide, and the combined action of the dissolved gas and water leaches out the soluble lime from the drift through which it filters. Since the north-central part of the United States experienced more than one ice invasion, and as the ice sheets advanced from different portions of Canada various types of glacial drift were deposited. The distribution of marl beds indicates a more

readily available supply of lime in some types of drift than in others. The relation of total soluble lime content to the amount leached, as represented by the amount of marl deposited, will be discussed later.

MANNER OF DEPOSITION

The processes involved in the deposition of $CaCO_3$ in fresh-water lakes are not thoroughly understood. It is agreed that lake waters charged with calcium bicarbonate deposit calcium carbonate when carbon dioxide escapes or is removed, but there is still some difference of opinion as to how the removal of CO_2 is accomplished. Of the theories advanced, none seems to account fully for the deposits of marl as they actually occur. The following processes have been suggested, and undoubtedly each has contributed to the deposition of some marl, but the relative amounts deposited due to each have not been determined:

a) The theory of direct chemical precipitation,[1] which attributes the loss of CO_2 to a decrease in pressure and an increase in temperature as the underground water issues into the lake basin.

b) The theory of biochemical precipitation,[2] which postulates that aquatic plants and animals, such as stoneworts and certain groups of algae, and also fresh-water molluscs, are instrumental in the extraction of lime from solution.

c) The theory of mechanical sedimentation, which supposes the lime of the marl beds to have been derived from the finely divided particles of crushed and ground limestone in the glacial drift, and to have been transported and deposited as a fine clastic sediment.

The manner of precipitation of marl may have no direct bearing on the relations between the occurrence of marl beds and types of glacial deposits, for conditions in shallow lake basins are very much the same for lakes in either sand or clayey moraines, in outwash plains, or in boulder till plains. The amount of lime brought to a given shallow basin seems to be a more critical, controlling factor.

[1] U. S. Blatchley, "Lakes and Marl Deposits of Northern Indiana," *Ann. Rept. Dept. Geol. Indiana 25* (1900), pp. 4–146.

[2] C. A. Davis, "Contributions to the Natural History of Marl," *Geol. Surv. Mich.*, Vol. VIII, Pt. III (1903), pp. 66–71.

DIFFERENT DRIFT SHEETS AS A SOURCE OF MARL

During the closing stage of the glacial epoch, the Wisconsin drift was deposited over most of the state of Minnesota. The ice sheets[1] (see Fig. 1) were as follows:

1. The Superior lobe of the Labrador ice sheet, an extension of ice southwestward from the Superior basin toward Mille Lacs Lake.

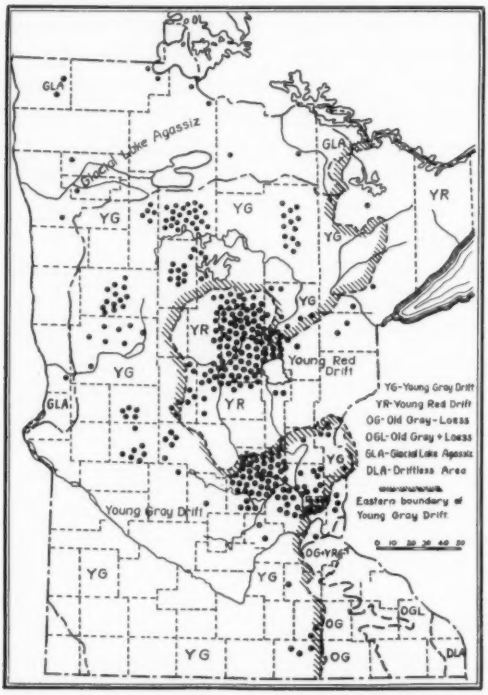

FIG. 1.—Outline map of Minnesota showing the general distribution of marl deposits.

2. The Patrician ice sheet with a southward movement from the highlands north of Lake Superior across eastern Minnesota to points a short distance beyond St. Paul.

[1] Leverett-Sardeson "Surface Formations of Minnesota," *Minn. Geol. Survey Bull. 14* (1919), p. 15.

3. The Keewatin ice sheet which moved southward through Manitoba and across western Minnesota.

The débris from the highlands of igneous and metamorphic rocks of the Lake Superior region forms the stony red drift of the eastern part of the state, while that from the limestone and shales of the Manitoba region forms the limy and clayey gray drift which covers almost all of the remainder of the state.

Since the various drift sheets are of sufficiently different composition to show variations in color, it is evident that they are also different in composition. Generally speaking, the gray drifts are clayey

TABLE I

SOLUBLE LIME CONTENT OF SAMPLES OF YOUNG RED AND YOUNG GRAY DRIFTS

RED DRIFT		GRAY DRIFT	
Sample No.	Percentage $CaCo_3$	Sample No.	Percentage $CaCo_3$
1	4.29	1	14.66
2	1.69	2	13.28
3	5.53	3	18.10
4	3.98	4	10.65
5	5.23	5	7.36
6	2.41	6	8.00
7	11.52	7	16.34
8	19.85	8	11.15
9	0.98	9	6.48
10	1.89	10	8.11
Average	5.73		11.41

and limy with comparatively few stones and boulders, whereas the red drifts are sandy or loamy and contain great numbers as well as great varieties of rock fragments, varying from gravel pebbles to boulders weighing many tons. From the difference in composition of the two drift sheets, it has been commonly assumed that the gray, limy drift would serve as a better source of marl than the red, stony drift from the Lake Superior region.

Analyses of fresh drift samples taken from widely separated areas indicate that the gray drift contains approximately twice as much soluble lime carbonate as the red drift. Table I gives the analytical results. However, in spite of a lower lime content, the red-drift areas contain a greater number and also larger deposits of marl than the

gray-drift areas. Figure 1 shows the relative abundance of marl beds in regions of the two types of drift. If the amount of available lime in a given drift sheet is not an index of the amount of lake marl that is deposited, factors other than composition of drift must be considered.

THE RELATION OF TEXTURE OF DRIFT TO MARL DEPOSITS

Glacial drift sheets may be divided on the basis of texture into clayey moraines and sandy or stony moraines; clayey till plains and sandy or stony till plains; and clayey outwash plains and sandy or gravely outwash plains. A study of the marl beds of thirty-five counties in the red and gray drift areas of Minnesota shows that the majority of the marl deposits are located in areas of outwash gravels and in sandy or stony moraines. Their locations with respect to the texture of the glacial deposits are summarized in Table II.

TABLE II

RELATION BETWEEN MARL DEPOSITS AND THE TEXTURE OF GLACIAL DRIFT IN THIRTY-FIVE COUNTIES OF CENTRAL MINNESOTA

Type of Glacial Deposit	Number of Marl Beds	Percentage of Total Number
Outwash sands and gravels	214	62
Sandy moraine	73	21
Clayey moraine	31	9
Till plains	27	8
Total	345	100

Since the greatest number of marl beds occur in regions where the surface formations are outwash gravels (Fig. 2), it may be contended that such formations cover the greatest amount of territory. A study of the drift shows, however, that outwash areas are not the most widespread of the surface formations. The clayey till plains cover a far greater number of square miles than any other type of deposit. The clayey moraines are also more abundant, and more widespread than the sandy and stony moraines. Yet more than twice as many marl beds are found in depressions in sandy moraines as in clayey moraines. One is, therefore, led to conclude that more

lime is leached from the glacial sediments that have a relatively coarse texture, even though the lime content of the drift is not so high, as from the fine-textured, clayey varieties that are typical of the young gray drift. In coarse, sandy drift more meteoric water

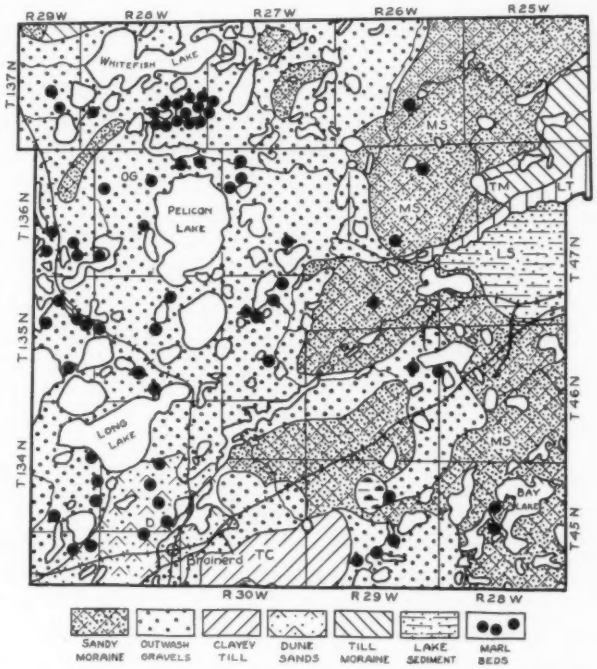

FIG. 2.—A region with outwash gravels and sandy moraine in central Minnesota. Note the greater number of marl beds in the outwash zone. (Drift classification by Leverett and Sardeson.)

seeps into the earth, and less joins the immediate run-off, than where the drift is a fine-textured, impervious clay (Fig. 3).

In order to compare the texture of different types of drift, a group of selected drift samples[1] was tested by screening. A 200-gram

[1] This experimental work was done by Mr. Lee Armstrong, under the writer's supervision, and was incorporated in a thesis on file in the Department of Geology, University of Minnesota.

sample was placed in a series of Tyler-scale screens and the set placed in a "Ro-tap" test screener and shaken for five minutes. The different mesh material was weighed and the percentage of material retained in each screen calculated. The cumulative percentage for each screen was also calculated by determining what part of the material would remain in a certain sieve if it were the only one used.

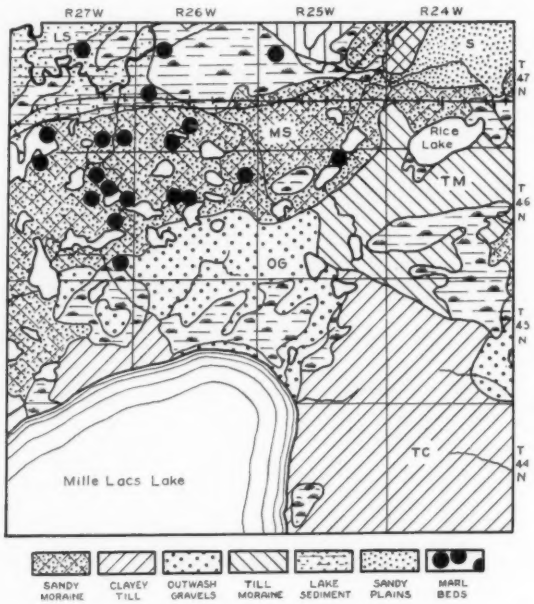

FIG. 3.—A region with sandy moraine and clayey till moraine in central Minnesota. Note the absence of marl beds in the clayey areas.

The results of these tests show that the red drift is uniformly coarser in texture than similar types of deposits of the gray drift.

By grading or screening a series of drift samples, it was also possible to determine in which sizes the lime values are concentrated. Each of the different mesh materials from the foregoing screening tests was analyzed for soluble carbonate. The results plotted in Figure 4 indicate that most of the lime is in the coarse fractions in

the form of small limestone fragments. All of the fractions finer than 100 mesh contained less than 5 per cent of lime carbonate.

Table III presents a comparison of the lime content of ground water from the young gray and the young red drifts. Calcium bicarbonate is more abundant in water in relatively deep wells in the gray drift. On the basis of such observations, more marl might be expected in the gray drift areas. However, the fine texture of the gray drift retards the circulation of the water to such an extent that only a small percentage of the lime reaches the lake basins.

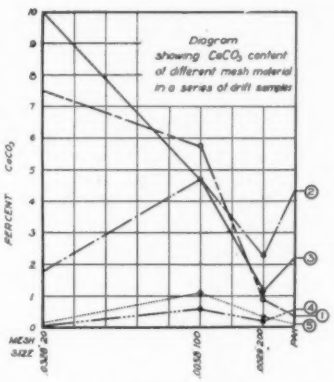

FIG. 4.—(1) Outwash sand and gravel from young gray drift; (2) morainic sand from young gray drift; (3) clayey terminal moraine of young gray drift; (4) clayey till from young red drift; (5) sandy till from young red drift.

THE EFFECT OF TOPOGRAPHY

In a region where the glacial drift has sufficient lime and its texture is favorable for the leaching of calcium bicarbonate, the character of the topography seems to be a factor in determining the number and size of the marl deposits. As already stated, most marl beds accumulate in depressions such as lakes, ponds, and shallow basins that were formerly occupied by lakes. Such depressions are characteristic of all areas of Pleistocene glaciation. However, it is found that the older drifts have been so extensively eroded and consequently so ramified by drainage lines that only a few undrained basins remain on their surface, whereas the younger drift deposits have numerous lake basins and large, poorly-drained areas which the streams have not yet reached. Nevertheless, in confining the study to areas covered by the youngest or Wisconsin ice sheet, it is noted that with other conditions favorable, the presence of high, rugged morainic hills favors the formation of large deposits of marl. The reason for this is undoubtedly the fact that morainic hills mean thicker drift and therefore a more extensive gathering ground for the leaching

solutions that carry dissolved mineral matter to the glacial basins. High rugged topography also tends to increase the hydrostatic head of the ground water, and this in turn increases the rate of circulation of the water. Since an increased rate of circulation of a solvent accelerates the rate at which a solute is dissolved, more lime is taken

TABLE III

LIME CONTENT OF GROUND WATER FROM WELLS IN THE GRAY AND IN THE RED DRIFT SHEETS

	Gray Drift Wells Lime in Parts per M.	Red Drift Well Lime in Parts per M.
	60	72
	103	60
	115	60
	97	57
	73	58
	22	70
	41	70
	115	84
	193	59
	9	68
	110	55
	44	55
	57	67
	88	82
	224	40
	65	71
	93	64
	115	48
	154	54
	88	50
Average.....	138	61

into solution in an area of moraine hills than in a region of slight relief, where the zone of vadase circulating is nearer the surface.

Artesian circulation in morainic deposits also favors the formation of marly sediments. In a number of localities, the structural relations of the glacial deposits are such that an impervious till overlies porous sands and gravels that are filled with water under considerable hydrostatic pressure. Where a glacial basin is sufficiently deep to allow such sands to outcrop on the floor or around the margins of

the basin, artesian springs discharge into the lake. This is strikingly shown in west-central Minnesota around Lake Minnewaska, where the water level of the lake is approximately 200 feet below the surrounding hills. Numerous springs occur on the hill slopes and flowing wells may be obtained at moderate depths, even at elevations several tens of feet above the level of the lake. Extensive marl beds have

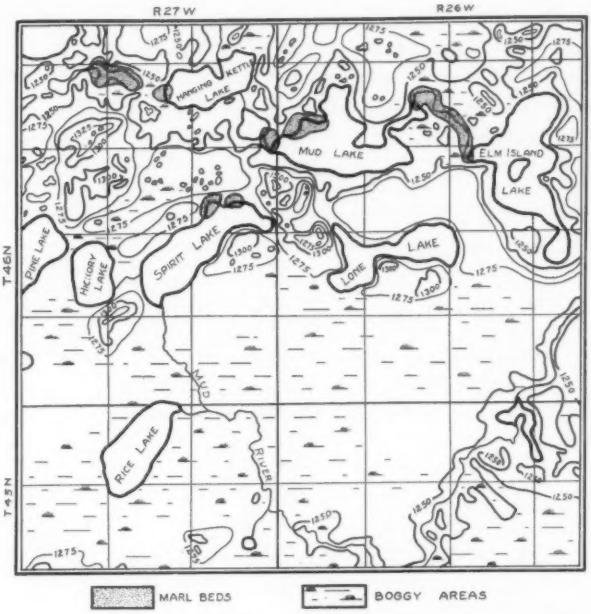

FIG. 5.—A zone of rugged morainic topography bordering an area with slight relief. Bogs and basins are present in both. Note that the marl beds are confined to the morainic zone.

been deposited around some of the springs and on the floor of part of the lake basin.

The association of marl beds with high morainic hills and the absence of such lime deposits in basins in flat, sandy areas may be shown in a great many localities. Figure 5 is a typical example. A zone of very irregular moraine hills crosses Aitkin County from east

to west in the region between Mille Lacs Lake and the valley of the Mississippi River. There are numerous marl beds in the basins among the hills, but none were discovered in the lakes that occupy basins where there is only slight relief. This correlation of marl with topographic relief is the opposite of what might be expected on the basis of the mineral content of ground water.

Dr. I. S. Allison[1] has recently shown that hard water is more prevalent in drift wells in flat regions than among morainic hills. This is undoubtedly due to the fact that ground water is more stagnant in regions of slight relief, and, therefore, eventually becomes more highly charged with mineral matter. However, very little of this water reaches the lake basins, and therefore little of its lime is extracted to form marl.

[1] Personal communication.

REVIEWS

Geography, Geology, and Mineral Resources of Part of Southeastern Idaho. By GEORGE ROGERS MANSFIELD. With Descriptions of Carboniferous and Triassic Fossils. By G. H. GIRTY. U. S. Geol. Survey, Prof. Paper 152. Pp. 453; pls. 70; 1927.

This monumental paper of Mansfield's is the result of many years' field work by Mansfield and other Survey geologists whose purpose was the examination of the phosphate rock resources of the region. Though the urge was economic, our knowledge of the northern Rockies has been immeasurably enriched by the studies of the physiography, stratigraphy, paleontology, and structure which accompanied the economic investigation. Brief reports and minor papers on parts of this area have been published by other authors from time to time. The information and conclusions contained in each of these are reviewed, revised, and summarized so as to fit into the masterful treatment of the entire area given by Mansfield.

Mansfield shows the Basin and Range province entering the mapped area on the west because of the postulated existence of block faults supposed to be characteristic of that province. Staff geologists of the Idaho Bureau of Mines and Geology have found two or more large overthrust faults in Bannock, Power, and Oneida counties on the west, apparently not typical Basin and Range faults, but more like those of the overthrust zone of the Middle Rocky Mountain province. Mansfield extends the Columbia Plateau province into the mountainous province, because several of the high mountain valleys are floored by lava streams which at their lower ends merge with the Snake River Plain. He says, "These valley extensions of the lava plain are properly arms or branches of it and as such they interlock with extensions of the Basin and Range province on the one hand and of the Northern Rocky Mountain province on the other." This assignment of the high mountain valleys to the Snake River plain is open to question on several grounds. It also raises the question as to the best criteria for determining boundaries of physiographic provinces. Is the presence of some type of rock sufficient for correlation? The source of the lava in most of these valleys is more than 2,000 feet above the point where the flows enter the plain. In no instance is the lava an embayment from the flows in the plain. Should not structure count for something in assigning physiographic boundaries? The high mountain valleys are

formed by faults and folds which join the plain at high angles. The plain itself is part of a vast and gentle downwarp, and has no genetic connection with the Middle Rocky Mountains or the mountain valleys within them.

On the other hand, the discussion of the physiographic development is masterful in the light of the spirited discussion of former years concerning Tertiary planation in Idaho and Wyoming. Mansfield's careful evaluation of the evidence in his region has contributed so greatly to the discussion that certain erosion surfaces in southeastern Idaho and Wyoming can now be safely alluded to without arousing controversy. That all of his surfaces, or erosion cycles, can be referred to other parts of Idaho is not so certain. He recognized a pre-Wasatch (Eocene) erosion surface, a post-Wasatch erosion surface and a Tygee erosion surface, a glacial episode, and the post-glacial stage.

The oldest surface has early mature topography and was formed in Cretaceous or earliest Eocene time. The Snowdrift peneplain was formed in Eocene time and is post-Wasatch. The Tygee erosion surface of relatively high relief was formed in Late Miocene or Early Pliocene time. Mansfield has assigned the term "cycle" to erosion surfaces which many geologists are prone to call peneplains in adjacent regions. This seems to be a very laudable attempt to restrict the term peneplain to those surfaces which are more than merely wide valleys.

Chapter iii ("Stratigraphic Geology," pp. 48–115) treats in detail the forty-one formations from Lower Cambrian to Recent. The section presents a thickness of 46,000 feet, and the distribution, lithology, thickness, paleontologic character, and age of each formation are carefully considered.

The Cambrian beds of this area represent 7,000 feet of quartzites, sandstones, limestones, and shales, distributed through seven formations. The Ordovician system includes 2,200 feet of gray limestones, quartzites, magnesian limestones and dolomite in three formations which contain Beekmantown, Chazy, and Richmond faunas. One dolomite of the Niagaran epoch is 1,000 feet thick and is the sole representative of the Silurian system.

The Devonian system includes 1,135 feet of limestone in two formations of Middle and Upper Devonian age. Following standard survey usage the rocks of the Carboniferous are referred to a system, and the Mississippian, Pennsylvanian, and Permian are described as series. Two limestones over 1,000 feet thick make up the Mississippian series. All of the Pennsylvanian rocks belong to one formation which varies from sandy to cherty and siliceous limestone with a maximum thickness of 2,600 feet.

The Permian rocks are contained in the Phosphoria formation. This contains the extensive deposits of high-grade phosphate rock of the great western field. The formation in general is less than 450 feet thick, but is very widespread and uniform in character. The soft phosphatic shales are overlain by the Rex chert member which is common throughout the region. Correlation is made with the Park City of Utah, the Embar of Wyoming, and questionably with the Upper Quadrant of Montana.

The Triassic system includes 5,350 feet of shales, limestones, and sandstones in five formations and also three formations including 550 feet of sediments provisionally assigned to the Triassic.

The Nuggett formation, at one time assigned to the Triassic system, is the basal Jurassic formation. This, with three other formations, one of which is a limestone, makes up a thickness of 6,700 feet.

The Cretaceous system includes the Gannett group of five formations tentatively assigned to the Lower Cretaceous(?). These are freshwater conglomerates, shales, limestones, and sandstones with a thickness of over 3,200 feet. Definitely established Cretaceous rocks are represented by the fresh-water Wayan formation which includes 11,800 feet of reddish sandstone, shales, and limestone, and some tuff. It is tentatively assigned to the Lower Cretaceous.

The Tertiary system includes the Wasatch of Eocene age, which consists of 1,500 feet or less of continental conglomerates, sandstones, and limestones. The Pliocene(?) series is represented by the widespread Salt Lake formation which consists of 1,000 feet or less of continental conglomerate, marl, clay, sandstone, and tuff. This formation beyond the boundaries of the map area is intimately associated with the widespread acidic flows which cover much of southern Idaho. The Quaternary rocks include extensive deposits of travertine as well as older hill wash and alluvium. Lake beds of older Bear Lake and recent alluvium and landslides complete the sequence.

Mansfield says on page 116, that the igneous rocks "represent chiefly, perhaps, marginal members or inflows of the great body of extrusive rocks that constitutes the so-called Snake River lava plains, but they have obviously come from local vents or fissures." These lavas are hornblende andesite porphyry, rhyolite, and olivine basalt. The andesite occurs in dikes, sills, and loccolith-like bodies and appears to be the oldest of the igneous rocks. The rhyolite occurs in cones, flows, and dikes(?) and is not to be confused with, or correlated with, the widespread acidic series which borders the Snake River Plain throughout nearly all of southern Idaho. The olivine basalt is the most widely distributed of the igneous rocks and

occurs in flows, cones, dikes, and ash beds. The flows originated from craters and extend to lower levels in all directions from the source, but in nearly all cases they extend much farther in the direction of the border of the Snake River plain which in all cases lies several hundred to two thousand feet lower than the local vents. In all, Mansfield recognizes at least six epochs of igneous activity with the possibility that three more epochs may eventually be proven. He is inclined to the view that the andesites and rhyolites originated from an earlier magmatic body underlying the region, and that the basalt has arisen from a later magma body, although he concedes that both rhyolites and basalts may represent differentiations from a single magma of intermediate composition. Studies by the reviewer of other parts of southern Idaho indicate that these three groups are rather general in distribution. An earlier andesitic, and at places, acidic series has been referred to the Early Tertiary. These rocks are evidently Miocene, or older, as indicated by field relations. A later Tertiary series of rhyolites and trachytes, more widespread in occurrence, was assigned to the Pliocene because of their interbedded relations to the Salt Lake Pliocene(?) formation and its relation to Pliocene lake beds in southwestern Idaho. The Snake River basalts are chiefly Pleistocene, although the earliest flows may have been Pliocene. At several places notably angular unconformities separate the three lava series north of the Snake River plain and the two later series south of the plain. Inasmuch as several million years apparently have intervened between these epochs of extrusion, it seems likely that more than one body of magma may have supplied the three lava series.

The structure of the region in general is similar to that of the southern Appalachians, being characterized by folds and faults of great magnitude. The individual folds of the synclinoria and anticlinoria are mostly asymmetrical, or overturned, and lie in nearly parallel belts. Inverted fan folds and "swallowtail" folds, normally rare features, are common here. Particularly important is the detailed description of the great Bannock overthrust, first described in 1912, which has been restudied. The northern trace of this fault, south of the Snake River plain, plunges beneath the lava near Blackfoot Peak and Idaho Falls. North of the lava plain a great overthrust which possesses identical relationships and similar majestic proportions occurs on Medicine Lodge Creek and extends northward beyond Dillon, Montana. It was tentatively suggested by Kirkham in 1927 that this may be a continuation of the Bannock overthrust. From Blackfoot Peak southward the Bannock occurs chiefly as a zone of branching overthrusts, or rock slices, with extremely low-angle planes dipping to

the west. In general Paleozoic strata are thrust to the east or northeast over Mesozoic strata. The maximum stratigraphic throw was at least 20,000 feet. The minimum horizontal overthrust was 12 miles and the maximum was more than 35 miles, allowing nothing for recession by erosion along the eastern margin. The length of this fault south of the plain is fully 270 miles. If the Medicine Lodge fault, north of the plain, is a continuation of this great structural feature, its length must be extended more than another 100 miles. More than a dozen other prominent thrust faults have been named, mapped, and described; all of these are thrust, like the Bannock, from the west to east, or northeast, and possess low-angle planes. Mansfield suggests that some of them may be branches of the Bannock thrust. It is his belief that some underthrusting, as well as overthrusting, may have occurred in the development of the great thrust fault. Superimposed on the overthrust lip of the Bannock are normal faults, with stratigraphic throw of 3,000 to 4,000 feet, which have developed horst and graben structure in parts of the region and have greatly displaced the low-angle planes of the thrust faults. The inferred traces of many of these normal faults lie chiefly beneath valley basalts and Quaternary hill wash and alluvium in which they are not expressed, and the patterns assigned to them, as for example in the Henry quadrangle, would be considered extremely bold and imaginative had the mapping been executed by a worker of less conservative reputation than Mansfield.

At least five mountain-building periods are noted, as follows: The Late or post-Jurassic (Nevadan); the Lower or Middle Cretaceous; the post-Cretaceous (Laramide); the post-Middle Miocene; and the Late Pliocene or Early Pleistocene deformation. The more important of these five were the post-Cretaceous and post-Pliocene revolutions. The former was responsible for the great overthrusts and major folds resulting from intense tangential pressure. The later manifestation was chiefly one of broad regional uplift, recurrent movement along the lines of the earlier deformation, and the development of minor undulations, such as those in the fault plane of the Bannock overthrust.

A tensional phase, in which some of the normal faults were formed, occurred between the two compressional phases. Subsequent to the last compressional phase occurred the chief tensional phase in which the major normal faults were developed. Rhyolite and basalt extrusions accompanied the last tensional phase and the extrusions are believed by Mansfield to have found their way to the surface along the normal and thrust-fault planes.

In the chapter on historical geology the sequence of events is described

in detail and compared with that of adjacent areas, as well as remote regions. Proterozoic rocks are not found in the region, but the Paleozoic era has a rather full record of dominantly marine deposition in a progressively subsiding geosyncline. Interruptions of sedimentation were relatively unimportant. Limestones dominate the section. Brief erosion intervals marked the close of the Cambrian, the Upper Ordovician, Upper Silurian, Lower Devonian, close of the Devonian, Middle Mississippian, close of the Mississippian, and the close of the Permian.

The change from the Paleozoic to Mesozoic in this region is marked by faunal rather than stratigraphic breaks. The Mesozoic as a whole is characterized by alternating marine and nonmarine deposition with the latter dominating toward the end of the era. Marine embayment continued throughout Lower Triassic times and was followed by an epoch of erosion and the deposition of continental red beds. In the Lower and Middle Jurassic these conditions were continued, but in the Upper Jurassic occurred the encroachment of the marine "Logan Sea" from the north. An interval of erosion was followed by another brief marine invasion before the period ended. An abrupt change in the character of sediments marks the transition to the Cretaceous. The Lower Cretaceous section comprises beds of fluvatile and lacustrine origin. A marked change, including major folding, occurred between Lower Cretaceous and Upper Cretaceous sedimentation in nearby areas. The Upper Cretaceous in the map area was a time of erosion. The Laramide revolution closed the period with the deformation of the geosyncline and the development of the Rocky Mountains and their attendant complicated structural features. An erosion interval intervened between the close of the Mesozoic and the deposition of Tertiary strata. In nearby areas this erosion interval is represented by a coal-bearing series of continental beds.

The Cenozoic was dominantly an era of erosion. Continental beds of the Wasatch (Eocene), the Salt Lake (Pliocene?), and the Pliocene(?) lava flows represent the chief formations of the era.

In a discussion of paleogeography the following ten principles are defined and discussed:

1. Permanence of ocean basins and continents.
2. Ocean basins the sources of major crustal disturbances.
3. Positive and negative elements.
4. Periodicity and rhythm.
5. Low ancient lands and shallow epicontinental seas.
6. Abnormal conditions of the present.
7. Continental and marine deposition.
8. Faunal realms.

9. Evolution and migration of faunas.
10. Imperfection of the record.

About three-fourths of the chapter on mineral resources is taken up in a detailed account of the physical, chemical, and geologic nature of the phosphate rock, the classification of phosphate lands, and descriptions of individual township occurrences with tonnage estimates. The phosphate occurs in the Upper Mississippian and more particularly in the Permian formations. The Idaho reserve comprises over 268,000 acres of phosphate land and over 5,000,000,000 tons of high-grade rock.

Perhaps the most interesting portion of this splendid work is the chapter devoted to "Broader Problems of the Region." Under "Physiographic Problems" Mansfield includes the much-debated Idaho Tertiary planation, the origin of the Snake River Basin and of the course of Bear River. Bear River, which heads in Utah and flows north into Idaho only to turn and re-enter Utah to debouch into Great Salt Lake, has its peculiar course explained by diversion of a Tertiary tributary of Snake River in consequence of uplift in Idaho. Mansfield concludes that the evidence for this portion of Idaho indicates planation of pre-Middle Miocene age. The reviewer believes that certainly two and probably three periods of planation are represented in Idaho, and that not all levels are represented in each area, and furthermore that the summit peneplain of one area need not necessarily be correlated with that in another portion of the state. Mansfield's analysis of the age of the summit peneplain in southeastern Idaho, however, seems undoubtedly correct.

The literature concerning the origin of the Snake River Basin is reviewed. Lindgren and Russell believed the present depression to have an Early Tertiary origin by faulting. Mansfield believes that the Snake River Basin is one of the oldest in southern and eastern Idaho and that it may date back to Eocene times. Other workers on this problem have concluded that the Basin was formed by downwarping, rather than by faulting, in Pliocene time.

The igneous rocks are compared with those of adjacent areas. In general the lack of volcanic activity at the time of deformation argues that these mountains belong to the "thin shelled" group defined by R. T. Chamberlin. The Cretaceous or Eocene age assigned by Mansfield to the Idaho batholith apparently leads him to assume that its intrusion was genetically connected with the formation of the Rocky Mountains of Idaho. Ross's recent paper has presented strong evidence, accepted by many, that the batholith is more likely Jurassic in age and that it is to be associated with the Nevadan rather than the Laramide revolution.

Under structural problems are considered the thrust-fault mechanics,

circumferential shortening, and tensional faulting. Mansfield believes the practically parallel overthrusts to be progressively younger to the east, and that overthrusting dominates underthrusting. He lists and describes briefly the more important overthrusts along the eastern side of the Rocky Mountain system from Montana to Utah. All of the north-south faults listed possess planes dipping to the west except the Willard overthrust in Utah. This is the westernmost of the listed faults and its plane dips to the east. This fault has been traced by the reviewer into Idaho to a point where it is masked by the Snake River lava flows. North of the Snake River downwarp at least three overthrusts have been described whose planes dip to the east. This recently acquired evidence offers persuasive argument that the Rocky Mountain system in this region is not a one-sided feature, but rather more nearly fits Chamberlin's wedge theory of diastrophism. In measuring the circumferential shortening Mansfield does for this region what Chamberlin did for the Appalachian folds in 1910, and the Colorado Rockies in 1919. Mansfield's analysis shows a shortening of over 52 per cent by folding and thrust faulting for the part of the Rockies included in his study.

The final discussion in this section includes major theories of mountain building. In this he has reviewed current ideas on "floating" continents and on isostasy as a mountain-building force, as well as theories of orogeny by Suess, the Chamberlins, Heim, Kober, Hobbs, Willis Daly, Bowie, Keith, Reid, and others. After considering carefully the various hypotheses Mansfield says, "The segmental hypothesis of T. C. Chamberlin and the wedge theory of R. T. Chamberlin seem to explain the facts better."

The bibliography includes about 340 excellent references, although unfortunately only 18 of these are of later date than 1922.

An appendix by George H. Girty describes in thirty-five pages fifty-one new species, or new varieties, of Carboniferous and Triassic fossils.

The publication is effectively illustrated by seventy plates and forty-six figures, including some beautifully reproduced colored geologic maps and structure sections. Summaries at the beginning of chapters serve as excellent guides to the factual and theoretical data within the paper. A carefully compiled table of contents and index make the data readily accessible. The paper may be secured from the Superintendent of Documents for $2.40 per copy. This comprehensive work is by far the most valuable contribution to our knowledge of the geology of the Northern Rocky Mountain region which has yet appeared.

VIRGIL R. D. KIRKHAM

Two Polar Maps, with Notes on Recent Polar Explorations. American Geographical Society Special Publication No. 11.

It is fortunate that the American Geographical Society has in recent years particularly devoted so much attention to exploration of the polar regions, since this has resulted in the issue of important monographs and of valuable maps. The latest issue of the Society is a pamphlet containing a revised map of the Arctic region and a new map of the Antarctic area, accompanied by a fifty-page pamphlet describing the maps and outlining the greater new discoveries within polar areas.

These maps are very valuable, setting forth particularly the results of areoplane and airship flights, but they leave a great deal to be desired through their failure to take account of much important earlier explorations, particularly British expeditions. It serves only to accentuate the bewildering rapidity with which new discoveries are being made, that though this publication was issued in 1930, no less than three new discoveries of inland-ice within the Antarctic region—and these of the greatest importance—have occurred too late to be included. These are Mawson's landfall between Queen Mary Land and Enderby Land, and Riis Larsen's two landfalls about equally spaced between Enderby Land and Coats Land.

For the Arctic maps the base of the latest edition of Dr. Andree's *Handatlas* is made use of. Exploration data have been entered upon this base and the place names given an English spelling. The editorial revision of this map shows a great many gaps. Where such vast unknown areas exist it is best to indicate the tracks of expeditions, and in general this method has been used. No account is taken, however, of the Greenland expeditions of De Quervain and Stollberg in 1909, or of Bangsted's and Wegener's expeditions over the inland-ice of Greenland east of Umanak in 1926 and 1929, or those of the University of Michigan from 1926 to 1929. Though a special inset map of Svalbard (Spitzbergen) is included, no account is taken of two transections and an additional penetration of Northeast Land by Binney's Oxford Expedition of 1924, or even of that by Nordenskiöld and Palander in 1870.

On the Antarctic map, where such relatively small areas have been seen by explorers, it is even more important that their tracks should be entered upon the map. The makers of the Antarctic map, however, have chosen rather to sketch in topography and indicate the known areas by a darker shade of color. This shade has in several instances not been extended over areas which have been seen; such, for example, as the routes of Armitage and Scott west of McMurdo Sound (First Scott Expedition), that of Prestrud of the Amundsen South Pole Expedition, or Bage across King

George Land to near the South Magnetic Pole (Mawson Expedition). Dr. Gould has shown that Carmen Land does not exist, but this is reprinted possibly because the information arrived too late to be made use of. An extraordinary northward projection of the land between the Liv and the Beardmore glacier outlets from the inland-ice is entered on the map with a query.

The known portion of the Ross Barrier shelf-ice could easily have been indicated by entering the tracks of the several British expeditions from the bases on McMurdo Sound, but only that of Admiral Byrd is entered. The important area of shelf-ice studied by the late Dr. Nordenskjöld southeast of Graham Land is not marked, though its character as shelf-ice has been confirmed by Wilkins.

"Antarctic Archipelago" is suggested as a tentative name for Graham Land. To the reviewer this seems an excellent suggestion for the entire archipelago, now that it has been found not to be a peninsula; but this makes it even more imperative that we retain the older names, such as Palmer and Graham Land, for the individual islands. These earlier names were applied to limited sections of coast land only, but their abandonment now would do violence to the rights of priority everywhere recognized.

WILLIAM H. HOBBS

The Evidence of the Kimberlite Pipes on the Constitution of the Outer Part of the Earth. By PERCY A. WAGNER. *South African Journal of Science*, Vol. XXV. Johannesburg, 1928. Pp. 127–48.

A study of the kimberlite xenoliths indicates rather definitely that an enormous area in Southern Africa is underlaid by layers of successively more basic rocks, from granite through gabbro or amphibolite to eclogites and peridotite. The peridotite layer lies at a depth of 60 kilometers or more, as indicated by the formation of diamonds and by some other evidence. Above that level there is no basaltic glass. The text is marred by confusing errors of expression, some of which are not merely typographical.

A. O. WOODFORD

New Brunswick, its Natural Resources and Development. By L. O. THOMAS. Natural Resources Intelligence Service, Ottawa, Canada, 1930. Pp. 166; photos, 33; sketch maps, 10; a general map in color.

A chapter of thirty-one pages gives a succinct statement of the general geology and mineral resources of the province. A map of the rock systems and another of the mineral occurrences will prove useful.

R. T. C.

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